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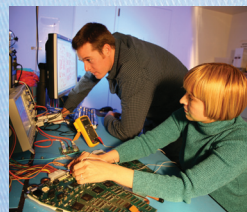
Experimental Physical Sciences

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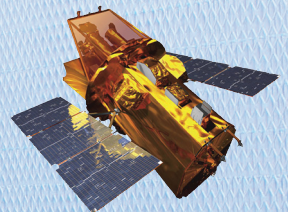
Los Alamos NPAC Research



Nuclear
science and
applications



Nuclear
and particle
physics



Astrophysics
and
cosmology

Los Alamos
NATIONAL LABORATORY

Explorations in nuclear and particle physics, astrophysics, and cosmology



A strategy motivated by scientific inquiry and national security priorities

In many ways, Los Alamos National Laboratory grew up along with nuclear physics. Nuclear physics was born in the early 20th century with the discovery of radioactivity, the nucleus, the neutron, and ultimately of nuclear fission. These discoveries and the onset of World War II led to the establishment of Los Alamos to harness the power of fission. The most renowned nuclear physicists of the time and the field's future leaders came to Los Alamos to work on this challenging mission—Bethe, Fermi, Oppenheimer, and Feynman.

Nuclear physics remained a central discipline of the Lab in the years after the Manhattan Project. Staying at the forefront of that field led Louis Rosen to propose LAMPF (Los Alamos Meson Physics Facility)—the first meson factory and first national-scale facility in nuclear physics in the United States. That facility lives on today as LANSCE (Los Alamos Neutron Science Center)—the Laboratory's signature experimental facility providing protons and neutrons to multiple disciplines.

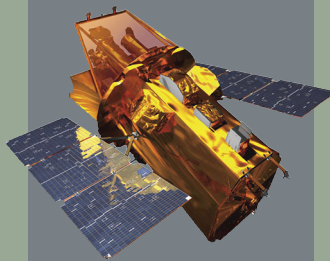
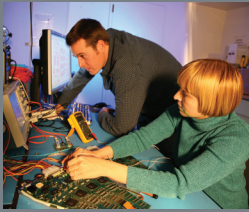
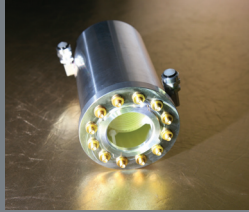
Los Alamos National Laboratory researchers continue to explore nuclear science and the physics that governs the universe. Through our continued research in nuclear physics, particle physics, astrophysics, and cosmology (NPAC), Los Alamos has established a distinguished history and strong reputation, driven not only by intrinsic scientific value, but equally by the relevance of these disciplines to Los Alamos National Laboratory's programmatic mission. Because of this, we have developed an institutional strategy for this area of research—linking the need to address the most important scientific questions in nuclear physics, particle physics, astrophysics, and cosmology and the need to apply the capabilities developed to core Los Alamos national security missions.

We have developed our strategy in the context of national decadal priorities documented in the following studies: (1) *US Particle Physics: Scientific Opportunities, A Strategic Plan*; (2) *The Frontiers of Nuclear Science, A Long-Range Plan*; and (3) *Astro2010: The Astronomy and Astrophysics Decadal Survey*. We integrated this input with our own mission considerations to guide our investment priorities. The purpose was to develop strategic priorities for a balanced, high-quality, relevant, and sustainable NPAC capability, a strategy that builds on our expertise in planning and project execution, the strength and diversity of our relationships with external collaborators, and our recognized vision in developing programs that employ our unique capabilities to address grand scientific challenges and support the nation's security needs.

Chronicled in this issue of *Experimental Physical Sciences Vistas* are the overviews of nuclear and particle physics, astrophysics, and cosmology experiments, models, and theory that form the core of NPAC research at Los Alamos. This research area has a long history of bringing the best and brightest scientists here and of making game-changing contributions to our national security mission.

I believe that the future is bright for this broad area of research.

Susan J. Seestrom
Associate Director Experimental Physical Sciences



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ON THE COVER

Los Alamos National Laboratory Director's Postdoctoral Fellow Rhiannon Meharchand assembles part of a new, compact time projection chamber being used for precision fission measurements at the Laboratory's Weapons Neutron Research facility at LANSCE. With it, scientists will have a better understanding of nuclear fission events, benefiting both Defense programs and Nuclear Energy programs.

Grand challenge science supporting national security

The nuclear physics, particle physics, astrophysics, and cosmology (NPAC) capability at Los Alamos National Laboratory has a rich tradition of attracting and supporting some of the best scientists in the world to conduct fundamental research and to direct those talents to support the Lab's national security science mission. Early luminaries such as Enrico Fermi and Hans Bethe were world renowned before they came to Los Alamos to work on the Manhattan Project; Fermi for his skills in experimental and theoretical nuclear physics and Bethe for his theoretical skills in nuclear physics and astrophysics—skills that were critical in the development of nuclear weapons. Later, as an outgrowth of their weapons physics research, scientists Frederick Reines and Clyde Cowan made the first confirmed measurement of the elusive neutrino, a discovery that led to Reines receiving the Nobel Prize in Physics in 1995. (Cowan died in 1974 before he was recognized for his contributions.)

Research conducted at Los Alamos today continues to rely heavily on the NPAC capability to attract and retain scientists with the expertise required to contribute to national security science, whether through programmatic-sponsored endeavors or through fundamental research into the grand scientific challenge of physics beyond the Standard Model. Our scientists conduct their research at the unique facilities found throughout the Laboratory and take advantage of other national and international facilities to obtain the best possible experimental results.

Nuclear science and applications

Understanding nuclear reactions, fission, and neutron transport—important to the function of a nuclear weapon fission-based primary—are topics of research at the Weapons Neutron Research facility, located at the Los Alamos Neutron Science Center (LANSCE). This research requires sophisticated instruments such as the Device for Advanced Neutron Capture Experiments and the Time Projection Chamber, a collaborative effort between Los Alamos National Laboratory, Lawrence Livermore National Laboratory, and many universities. Using the thermal-to-high-energy neutrons produced in spallation targets by the LANSCE accelerator proton beam, researchers make precision measurements of neutron capture and fission cross sections that are important to weapons performance and forensics, nuclear energy, and fundamental stellar nucleosynthesis processes. The Proton Radiography (pRad)

facility creates the one-of-a-kind-in-the-world capability of using the direct proton beam to produce a multiple time series of high-quality radiographs of dynamic processes relevant to the weapons program. And, using the pRad capability, Global Security programs have tested active interrogation strategies for detecting smuggled nuclear materials. At the Isotope Production Facility, Los Alamos researchers irradiate a variety of targets and produce various short-lived isotopes important for nuclear medicine and research.

Nuclear and particle physics

The world's highest density source of ultracold neutrons is found at the Ultracold Neutron facility, an environment beneficial to studies of symmetries in neutron beta decay and the surprisingly poorly known lifetime of the neutron, physics research that is complementary to that ongoing at Europe's Large Hadron Collider at CERN.

At Brookhaven National Laboratory, Los Alamos researchers conduct experiments on the Relativistic Heavy Ion Collider (RHIC) to understand the properties of cold nuclear matter as well as the properties of the quark-gluon plasma. At the Fermi National Accelerator Laboratory, Los Alamos scientists using MiniBooNE have uncovered intriguing hints of neutrino oscillations implying the existence of sterile neutrinos—neutrinos that interact even more weakly than the standard neutrino. If confirmed, this observation would be as exciting as the original Nobel prize-winning discovery of the neutrino. Plans are under way to utilize the accelerator's neutrino source to send a beam to a detector installed hundreds of miles away in a former South Dakota mine turned underground laboratory. The Long Baseline Neutrino Experiment would help pin down the remaining properties of the accepted three generations of neutrinos. And Los Alamos scientists are developing a technique to detect dark matter, one of the major—yet unknown—constituents of the universe. MiniCLEAN, a liquid neon or argon detector, has the possibility of being scaled to the 50-ton size that is thought to be required for a definitive measurement of dark matter.

Astrophysics and cosmology

Understanding the science behind highest energy processes in the universe is key to both astrophysics and nuclear

weapons. As such, Los Alamos has a rich history in such research, beginning with the early days of the Manhattan Project.

At the nearby Fenton Hill, at an elevation of 8,700 feet, Los Alamos scientists used the Milagro Gamma-Ray Observatory to explore fundamental properties of very high-energy cosmic rays, providing insight into the physics of the highest energy astrophysical properties of the universe. Now, they lead an international collaboration of scientists on the High-Altitude Water Cherenkov Gamma-Ray Observatory (HAWC), an observatory under construction at an elevation of 13,500 feet in Mexico. HAWC will be 15 times more sensitive than Milagro and is designed to discover the origins of cosmic rays.

Today, the Swift spacecraft is the premier observatory for the study of gamma-ray bursts. Los Alamos scientists played a large role in the mission's design and developed the software that automatically triggers, identifies, and locates the gamma-ray bursts so the spacecraft can be repositioned for further observations with more sensitive telescopes. The RAPid Telescopes for Optical Response (RAPTOR) system, also developed by Laboratory researchers and located at the Fenton Hill site, is comprised of several coupled wide-angle telescopes, configured to rapidly respond to notifications from Swift to measure the optical emission from gamma-ray bursts that carry the signature of the explosion. RAPTOR also maps the night sky in search of transient optical events of astrophysical significance. Finally, RAPTOR is also used to detect and track man-made objects in orbit to provide information on the near space activities of potential threat countries.

Underpinning all of these experimental efforts are the theoretical and computational efforts in nuclear physics, particle physics, astrophysics, and cosmology.

Using the Laboratory's unrivaled theory, modeling, and simulation capabilities, Los Alamos scientists seek to understand fission, nuclear structure, and cross-sections relevant to weapons physics in work directly complementing measurements made on these processes at LANSCE. Related theoretical work on nuclear astrophysics and stellar astrophysics strives to understand gamma-ray bursts and their observational properties as well as stellar structure and nucleosynthesis. Theoretical research in beyond the Standard Model physics concentrates on lattice gauge calculations to help understand the quark-gluon plasmas produced at RHIC and possible neutrino theories and processes to aid in interpreting and understanding the measurements made at the Fermi accelerator. Astrophysical research, both in very high-energy particle physics and in high-temperature plasmas,

is conducted to understand the very high-energy processes observed at Milagro and soon to be discovered at HAWC. All of these efforts take advantage of supercomputing capabilities that enable sophisticated weapons calculations.

At Los Alamos there is a cooperative spirit behind the work that brings together ideas, techniques, and people enabling both pure and applied research to progress faster than would be otherwise possible.

The NPAC capability has enabled the recruitment and retention of some of the best scientists in the world to meet the needs of the Weapons and Global Security programs at Los Alamos. This issue of *Experimental Physical Sciences Vistas* highlights the fundamental and applied science contained within the NPAC capability and showcases the excellent work ongoing in support of both.

The research featured in this publication is sponsored by

Laboratory Directed Research and Development

DOE NNSA Defense Program Science Campaigns

DOE Office of Nuclear Energy

DOE Office of Science, Office of Fusion Energy Sciences

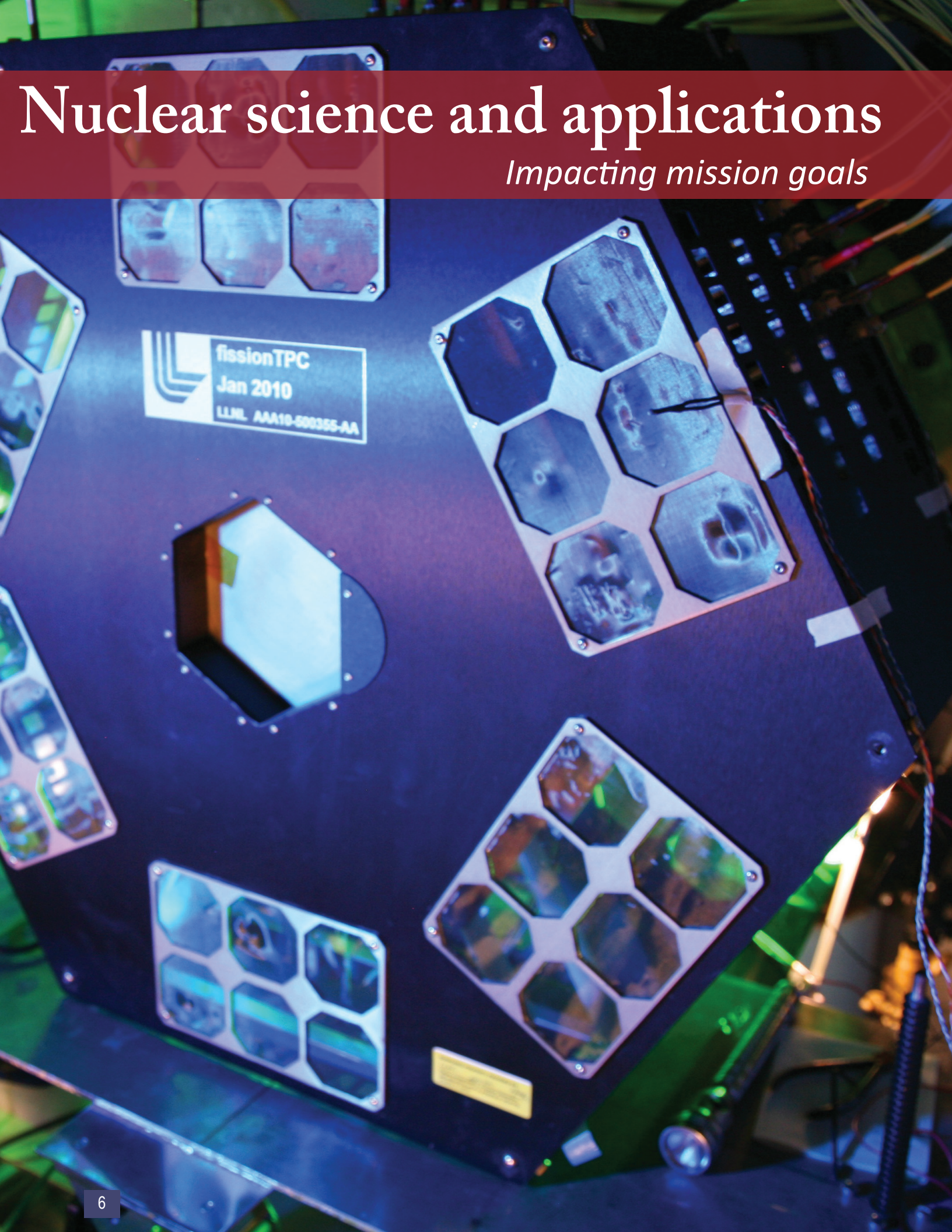
DOE Office of Science, Office of High Energy Physics

DOE Office of Science, Office of Nuclear Physics

National Science Foundation

NASA

CEA involvement is under the auspices of a CEA La Direction des Applications Militaires (DAM)/DOE NNSA international agreement on cooperation in fundamental science



Nuclear science and applications

Impacting mission goals

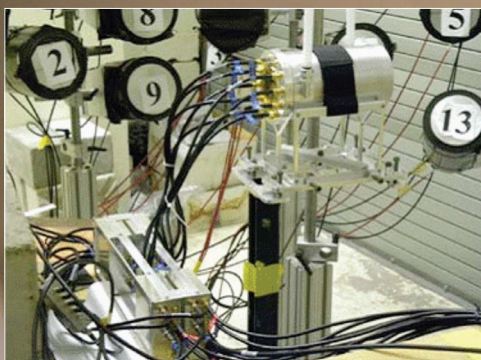


Nuclear physics and radiochemistry have been fundamental

to the Laboratory's mission since its inception. Indeed, certification of the enduring stockpile depends upon the quality of complex simulations and the accuracy of data upon which those calculations are based. Similarly, understanding nuclear threats from foreign and non-state-sponsored groups also relies on complex simulations that may have different requirements from those needed for the stockpile. The successful design and modeling of next-generation nuclear power reactors also depends on having accurate data for fission and a variety of nuclear reactions. Production of radioisotopes for medicine and research is an essential element of a program to understand and use nuclear reactions for applications and fundamental science. All of these coalesce at LANSCE to create opportunities for research in support of national goals.

With unique facilities and capabilities, including the intense broad-spectrum neutron sources at LANSCE, processing and handling capabilities for radioactive materials, and state-of-the-art instruments, Los Alamos National Laboratory continues to lead in providing research results and opportunities for the nation and the world. The nuclear physics capabilities at the Laboratory have research programs that yield a wealth of vital data on neutron-induced reactions for a wide range of basic and applied research and for theoretical model development. These measurements include reaction rates (cross sections), nuclear spectroscopy, lifetime measurements, and more. These data have direct application to defense programs by addressing issues that affect certification, from providing data for accurate modeling and simulations to understanding diagnostics from the Nevada Test Site data archives. Measurements at LANSCE also benefit energy programs, through the advanced and conventional reactor programs, as well as global security for nuclear materials detection and forensics, and medical radioisotope production. These ongoing projects directly support the NPAC goals of executing an astrophysics program that produces impact science and significant national security programmatic contributions, and fosters and demonstrates major capabilities. Presented here are examples of noteworthy research projects with an emphasis on their connection to the Laboratory mission.

The Time Projection Chamber, a collaboration between Los Alamos and Lawrence Livermore national laboratories and universities, is used to precisely measure fission cross sections.



Research in support of national security programs

Certifying the nuclear stockpile requires accurate simulations. These simulations depend on a wide range of data on materials properties from the atomic and molecular scale to the nuclear scale. As progress leads to refinements in one area, such as better understanding of material equation of state at high pressure and temperature, similar advances in other properties, such as nuclear reactions, may be needed to increase our level of understanding of how weapons work. In the past decade, reduction of uncertainties in a number of nuclear reaction properties helped advance our predictive capabilities for nuclear weapons. Present limitations arise most notably from fission uncertainties that are being addressed by current efforts at LANSCE.

Energy production and cross sections

Nuclear fission is the driver for the immense energy production in nuclear weapons. The complex and challenging measurements required to understand the fission process are the focus of the Time Projection Chamber and Chi-Nu projects.

A fission time projection chamber (TPC) has been designed and is under construction. Lawrence Livermore National Laboratory, Los Alamos National Laboratory, and multiple universities are working together on the effort, which is funded by both the Department of Energy (DOE) Office of Nuclear Energy under the Fuel Cycle Research and Development program and the National Nuclear Security Administration (NNSA) Defense Program Science Campaigns. The TPC is designed to allow more precise fission cross-section measurements than were possible with previously used techniques, benefiting both Defense programs and Nuclear Energy programs through increased understanding of energy generation and accuracy in modeling of reactors and weapons. For more information on the TPC project and its initial results, please see page 14.

The goal of the Chi-Nu project is to measure the energy spectrum and number of neutrons emitted in fission. Achieving the accuracy required is challenging in this type of measurement. One key element is the construction of a new building with a pit below the neutron detectors. The pit and its dimensions are crucial to success by removing backgrounds that would result from neutrons scattered into the detectors from the floor. The fission detector for the measurement is being developed at Lawrence Livermore, and is designed to give an extremely fast timing signal and to have sufficient actinide sample material—both critical factors in reaching the stringent goals for accuracy. A team



A specially-designed fission detector for the Chi-Nu project, which aims to measure the energy spectrum and number of neutrons emitted in fission. The detector (above) is used at the center of an array of neutron detectors. A new array is under development that will have vastly superior measurement capabilities.

led by Los Alamos National Laboratory with members from Lawrence Livermore National Laboratory and collaborators from the French Commissariat à l'Énergie Atomique (CEA) is defining and developing the instrumentation and facilities for the measurement. Primary funding is from the NNSA Science Campaigns, with contributions from the DOE Nuclear Energy Program through the Nuclear Energy University Partnership. CEA involvement is under the auspices of a CEA La Direction des Applications Militaires (DAM)/DOE NNSA international agreement on cooperation in fundamental science.

Fission product yields

Accurately measuring the fission yield of a nuclear weapon is critical in understanding weapon performance. Fission yield is determined from the yield of several well-chosen fission product nuclei based on a great deal of careful work conducted during the years of nuclear testing at the Nevada Test Site. However, more work is needed to ensure accurate understanding of the yields. Los Alamos, in collaboration with Lawrence Livermore, is applying expertise in fission measurements to address the issues through projects that will provide a wealth of unique fission product yield data that will serve as a foundation for development of advanced fission modeling.

Radiochemical detectors and nuclear forensics

Elements, selected for their specific nuclear reaction and decay properties, were used in past nuclear weapons tests to provide information about the neutron environment in weapons. Debris was recovered after a test by drilling into the underground cavity created by the nuclear explosion and sampling material from selected locations. The debris was radiochemically analyzed to provide information on weapon performance. Accurate nuclear reaction rates are required to interpret these data—precisely the data that can be measured at LANSCE. Three instruments at LANSCE that researchers have used extensively to measure reaction rates for radiochemical detectors are the Detector for Advanced Neutron Capture Experiments (DANCE), Germanium Array for Neutron Induced Excitations (GEANIE), and the Lead Slowing Down Spectrometer (LSDS). These detectors provide new information on the reaction rates on both stable and unstable nuclei.

As is the case for a number of Laboratory capabilities, the value of nuclear science has increasingly been demonstrated in applications beyond the weapons program. Radiochemical analysis not only is useful in the evaluation of U.S. events, but it is increasingly being developed for application in the field of nuclear forensics; that is, the technical characterization of unknown events, such as a terrorist's use of

Weapons Neutron Research facility

A broad-spectrum, high-energy neutron source for science and national security

Using an unmoderated (bare) spallation target, the Weapons Neutron Research (WNR) facility produces neutrons with energies ranging from below 100 keV (kiloelectron volts) to above 600 MeV (megaelectron volts). The target consists of a small, water-cooled tungsten cylinder. Six neutron flight paths are available for simultaneous measurements. A new building (pictured below), funded by Los Alamos National Security, LLC, expands the capabilities at LANSCE and includes a low-neutron-return experimental area essential for the Chi-Nu fission neutron spectrum measurements (described on page 8), and doubles the flight path space available for studies of neutron-induced effects in semiconductor devices. Demand for semiconductor electronics testing on the previously available flight path exceeded availability. WNR is the first choice for testing of neutron effects on semiconductors—such as computer memory, avionics, and field programmable gate arrays—because the neutron energy spectrum closely matches the cosmic ray-produced spectrum. The WNR flight paths are used to measure properties of reactions produced by energetic neutrons including fission neutron output spectra (Chi-Nu), time projection chamber precision fission probabilities (cross sections), gamma-ray production with precise energy selection, and charged particle production rates. As well, they are used for applications such as neutron dosimetry, neutron detector testing, a variety of basic science research, and neutron damage to biological systems. NNSA Science Campaigns and Readiness in Technical Base and Facilities primarily fund WNR operations.



Lujan Neutron Scattering Center

A high-intensity, low-energy neutron source for science and national security

The Lujan Neutron Scattering Center moderated spallation neutron source is engineered to withstand a 100-kilowatt proton beam power irradiation while maintaining water and liquid hydrogen moderators in close proximity. The neutron source feeds 16 neutron flight paths, the majority of which are used for neutron scattering instruments under the DOE Office of Basic Energy Sciences materials research program. Three flight paths are dedicated to nuclear science measurements and include studies using the Detector for Advanced Neutron Capture Experiments (DANCE), fission cross-section measurements, and fundamental nuclear science studies. The Proton Storage Ring is an important feature of the Lujan Center. The ring delivers proton beam in tight bursts at a typical rate of 20 per second to the neutron production target. This rate provides ideal timing and neutron energy resolution for many of the research instruments and is flexible in allowing other rates for special needs. The short proton beam pulse length and the flexible delivery rate allow for unique applications, such as resonance studies and imaging, with much better resolution than is possible at Oak Ridge National Laboratory's Spallation Neutron Source, due to its longer proton pulse width.

View of Lujan Center instrument hall.



a nuclear device. This constitutes a different type of technical challenge from a U.S. weapons test, requiring modified radiochemical diagnostics for the different conditions in these threats.

Addressing these different cases requires improved nuclear data and new measurements that will enable us to uncover critical evidence about improvised, foreign, or other non-stockpile nuclear devices. This evidence can also generate information on the emplacement of a device or materials of construction, provided we have confidence in the accuracy and precision of measured reaction rates.

Global security

The neutron beams available for the testing and development of detectors at LANSCE aid efforts to enhance security both nationally and internationally, through the development of better monitoring techniques for protecting nuclear material and for detecting the movement or use of nuclear material. Development of dedicated neutron calibration and testing facilities is planned to address the need for fast and accurate detector characterization.

The development of new diagnostics for understanding unconventional nuclear events through simulation relies on accurate nuclear data that are often different from the data needed for stockpile systems. These needs are being addressed using DANCE for neutron capture measurements and the LSDS, TPC, and fission ionization chambers for fission cross sections. The challenges of identifying the materials, construction, and functioning of nuclear explosives of unknown design can be formidable and this area is expected to increase in importance.

Research enabling the future of nuclear energy

LANSCE is a prime source for much of the data needed for next-generation nuclear reactor design because of the neutron source's wide energy range coverage and LANSCE's experimental detector facilities. These designs will vastly reduce the nuclear waste problem by burning most of the long-lived and highly radioactive nuclei produced. This greatly enhanced reduction of nuclear waste will be accomplished by using higher-energy neutrons than conventional thermal reactors. For effective reactor design at higher neutron energies, more accurate data on fission and other neutron reactions at these higher energies are necessary for input into detailed simulation and modeling codes.

Nuclear reaction cross-section measurements

In addition to the TPC fission cross-section measurements detailed above, fission cross sections are also measured with ionization chambers at LANSCE. These data span the full energy range of interest from thermal to beyond the highest fast reactor spectrum energies. While there is overlap in the actinides of interest for Defense Programs and Nuclear Energy, interest in some minor actinides and in other nuclear reactions is different between the two applications. LANSCE is the only U.S. facility that can provide necessary data over the full energy range and the actinides of interest.

Precise data on nuclear fission are required for a variety of nuclei for the DOE Nuclear Energy program. Such data allow more accurate reactor modeling and simulations that are needed to design the next generation of nuclear reactors, as well as reducing uncertainties in understanding performance of operating reactors. Data on fission product yields is also necessary to understand the inventory of radionuclides produced in a reactor. Such simulation codes predict reactor performance, radiotoxicity, decay heat, failure scenarios, and more. A new Los Alamos fission product theory and measurement effort, funded internally, will benefit Nuclear Energy programs as well as Defense programs by providing detailed and accurate data where none exists and using the new data to guide the development of more accurate theories of fission.

Neutron-induced charged particle measurements at LANSCE are redefining our knowledge of important helium and hydrogen gas production rates in steel. The production of helium and hydrogen gas in nuclear reactor components, such as pressure vessels, due to high-energy neutron reactions is a significant component of radiation damage. The calculated lifetime and safety margins of steel pressure vessels depend directly on this information.

Using LANSCE for basic nuclear physics research

The capture of neutrons by nuclei in stars creates elements heavier than iron. Understanding the details of the production of the elements is one of the “Goals for the Century” of the National Academy of Sciences. The U.S. nuclear physics community is now focusing efforts on the Facility for Rare Isotope Beams (FRIB) that will extend our understanding of nuclei far from stability. Research with DANCE at LANSCE, provides information not only on stable nuclides, but on radioactive materials as well. This is an important capability because it is precisely the reactions on radioactive nuclei that are most difficult to determine

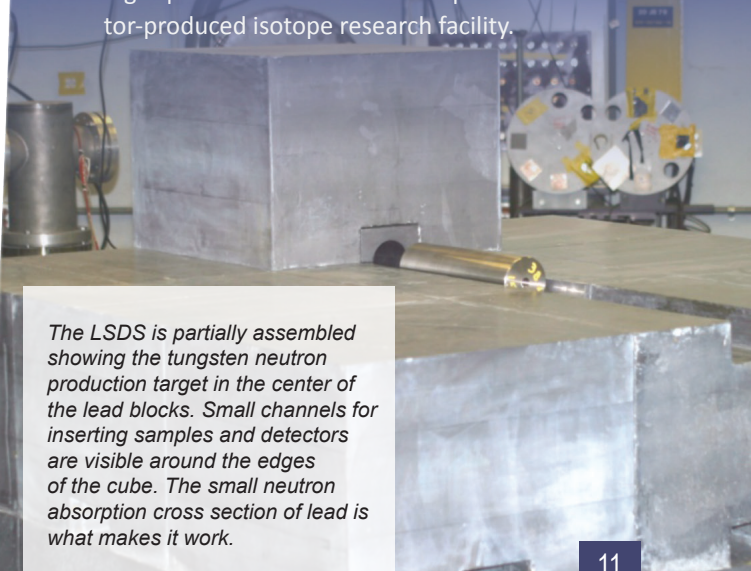
The Blue Room

Intense proton pulses for science and national security

Experiments using the direct proton beam are executed in the Blue Room. This includes operation of the Lead Slowing Down Spectrometer (LSDS), a device that achieves a high effective neutron flux by “recycling” neutrons in a large cube of pure lead. The flexibility of operating the proton accelerator at multiple energies from 250-800 MeV and delivering the beam to experimental setups either in vacuum or in air provides opportunities for research beyond those available with the spallation neutron sources. The proton beam in the LANSCE Blue Room provides intense proton pulses that the Oak Ridge National Laboratory Spallation Neutron Source (SNS) target team used to test designs for beam windows for the SNS liquid mercury spallation target. Erosion of the target windows under irradiation limits the time between maintenance periods for the SNS. The studies of mitigation techniques at LANSCE were crucial in addressing these issues.

The high neutron flux of the LSDS enables measurements of fission probabilities and charged particle emission from small and radioactive samples. The trade-off for the high flux of this instrument is the somewhat poor neutron energy resolution of about 30%. Current measurements are determining the neutron-induced fission cross section of uranium-237, which has a half life of about 1 week. The sample is produced and processed into a fission counter at Oak Ridge National Laboratory and transported quickly to Los Alamos for the measurement.

The Blue Room’s beam energy and irradiation flexibility make it an ideal place to measure cross sections of new isotopes of interest and complements the Laboratory’s Isotope Production Facility and radiochemical processing capabilities to achieve a comprehensive accelerator-produced isotope research facility.



The LSDS is partially assembled showing the tungsten neutron production target in the center of the lead blocks. Small channels for inserting samples and detectors are visible around the edges of the cube. The small neutron absorption cross section of lead is what makes it work.

The Proton Radiography facility

Imaging materials in extremes for fundamental and mission-related studies

Using the 800-MeV proton beam generated by the LANSCE linear accelerator, Los Alamos's Proton Radiography (pRad) national user facility provides access to a one-of-a-kind tool for dynamic materials studies, giving users a better understanding of the science and engineering of materials under extreme density, strain, and strain rate. This information helps Los Alamos maintain the reliability of the U.S. nuclear stockpile.

This facility is primarily used for studying the properties of high-explosives-driven systems through the collection of multiple radiographic frames, up to 42 images, during each dynamic event. Revolutionizing the capability of 800-MeV proton radiography, a new hybrid silicon-complementary metal oxide semiconductor camera system has recently been tested and prototyped at LANSCE, while a second generation of hybrid cameras, which will collect more than 60 frames per dynamic event, is being developed and fabricated.

The proton radiography system can be operated either in high-resolution mode, providing position resolution of almost a tenth of a millimeter, or large-aperture mode, proving a field of view of 12 centimeters. High pressures are obtained by using either high explosives or high-velocity projectiles, allowing the real-time study of material properties under extreme conditions. A 6-foot steel vessel with 2-inch-thick walls both contains the blast from up to 10 pounds of high explosives and allows the safe use of hazardous materials in experiments.

A view of the low energy drift tube section of the half-mile-long LANSCE 800-MeV linear accelerator.

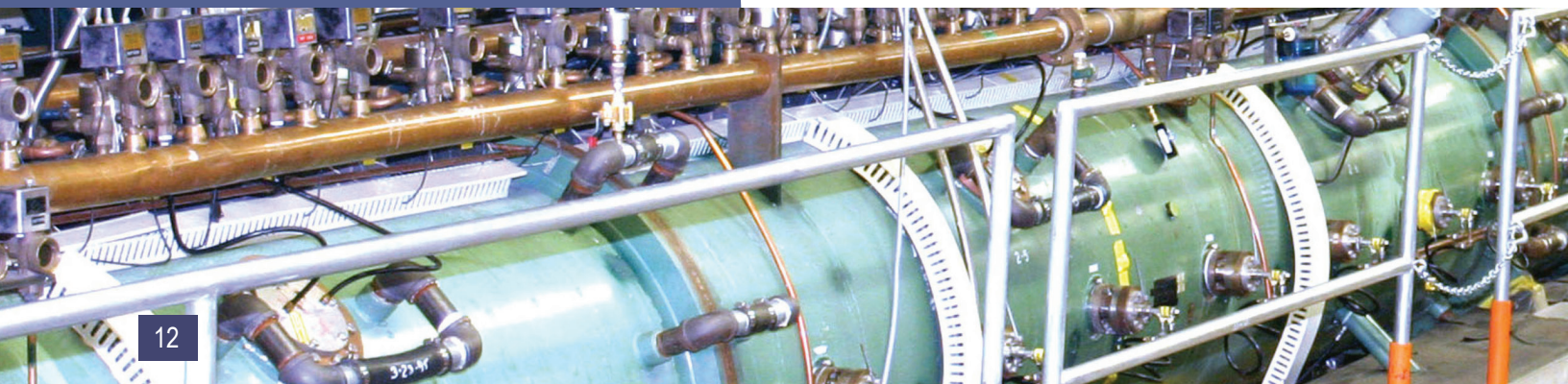
and that are important input to simulations enabling understanding of the production of elements in the stars. Recent experiments have demonstrated the feasibility of measurements on strongly gamma-ray-emitting samples with relatively short half lives. Taking on the more difficult cases of samples with shorter half lives expands the range of nuclei that can be studied to determine reaction rates important for understanding stellar production of elements.

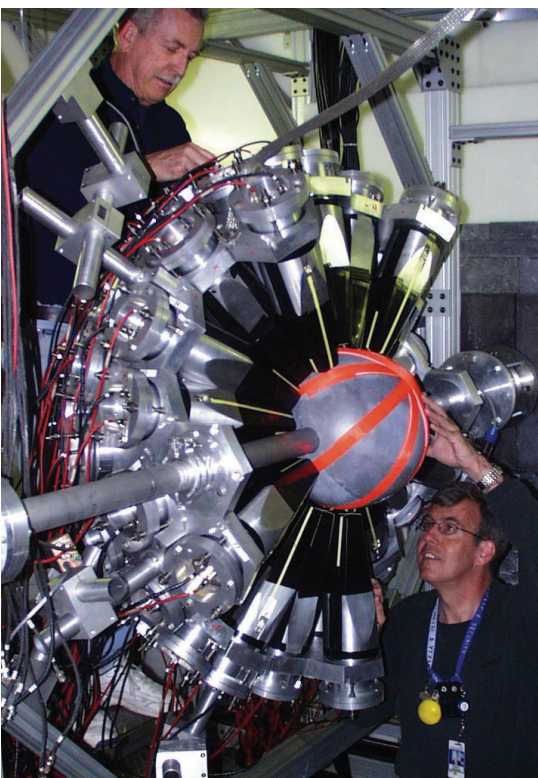
Isotope production for medical and research use

Medical and research isotopes are produced using the Isotope Production Facility at the 100-MeV accelerator station. This relatively new facility enables cost-effective and reliable isotope production over a longer running period to meet demand for medical diagnostics. Research into production techniques and uses of nontraditional radioisotopes for a wide variety of applications are planned as part of a robust isotope program. The Isotope Production Facility and related work are funded by the DOE Office of Science, Office of Nuclear Physics.

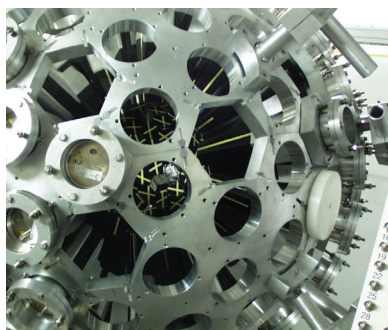
The future at LANSCE

LANSCE plays an important role today in meeting the needs of the nation and the world in providing nuclear data and measurement capabilities. LANSCE is key to the future science planned at Los Alamos. The development of advanced materials and a predictive capability for designing those materials are at the core of MaRIE (Matter-Radiation Interactions in Extremes), the Laboratory's vision for the future. LANSCE is an essential facility in realizing this vision. Self-healing structural materials for use in intense radiation environments, improvements in the lifetime of nuclear fuels, and understanding and improved design of radiation-resistant semiconductor devices are examples of research planned for MaRIE and LANSCE. The Laboratory continues to develop new capabilities, such as "pulse stacking," as a way to provide more intense and flexible neutron beams. These more intense neutron beams will enable a push into the frontiers of nuclear research that will allow the Laboratory to address the needs of the Nuclear Weapons and Nuclear Energy programs into the future.





The DANCE neutron capture gamma-ray detector array consists of 160 barium fluoride crystals that produce light when struck by gamma rays. This state-of-the-art detector and data acquisition system are designed for neutron capture measurements on very small (microgram) and radioactive samples.



Alignment marks on the crystal faces can be seen inside the DANCE detector framework.

The ability to make measurements on small radioactive samples sets DANCE apart from previous neutron capture detectors.

Detector for Advanced Neutron Capture Experiments

DANCE: A crystal ball for nuclear physics

The Detector for Advanced Neutron Capture Experiments (DANCE) is a world-class gamma-ray detector array for neutron capture measurements. Its 160 barium fluoride scintillator crystals cover almost a full sphere around the target, thus serving as a calorimeter to absorb the full energy emitted as gamma rays when a neutron is captured into a nucleus. DANCE's coverage of the wide neutron energy range provided by the Lujan source enables scientists to study neutron capture reactions in great detail for a range of science and applications. The ability to make measurements on small radioactive samples sets DANCE apart from previous neutron capture detectors. Applications include cross sections for radiochemical diagnostics for Defense programs and Nuclear Energy programs, and for nuclear astrophysics, thereby advancing the understanding of nucleosynthesis and the production of elements and isotopes in the stars.

Neutron capture reactions are essential to understanding the synthesis of elements in stars and the production of radiochemical diagnostic isotopes in archived nuclear weapon underground test data. In the explosive, neutron-rich environment of weapons and stars, neutron capture occurs on radioactive isotopes that often have rather short lifetimes. Because of the difficulty of producing and measuring neutron reactions on radioactive isotopes, few measurements have been made. DANCE is designed specifically to measure data on such unstable nuclei. These neutron reaction cross sections are vital input to simulations of weapons performance and nucleosynthesis in stars. Through contributions to the understanding of the synthesis of elements in stars, this work directly addresses the NPAC goal of leadership in astrophysics.

The combination of the intense neutron source at the Lujan Neutron Scattering Center and the DANCE array provides capabilities for neutron capture measurements rivaled only by the large neutron time-of-flight collaboration at CERN in Europe, which still needs much larger sample masses than DANCE. Because neutron capture reaction rates are sensitively dependent on properties of each isotope, it is one of the quantities that theory least accurately predicts, making accurate measurements and development of improved theories essential for progress.

As an example of neutron capture reaction measurements at DANCE, a new and potentially powerful diagnostic of underground nuclear tests is provided by americium-241, which is a decay product of the plutonium-241 present as an isotopic impurity in most plutonium. At DANCE, scientists measured the americium-241 neutron capture cross section more accurately than ever. These data enable the use of the new diagnostic with confidence. The americium-241 nuclide has advantages over previously used diagnostics.

For the development of advanced nuclear power reactors, the production and fissioning of minor actinides plays a larger role than for current power generating reactors. To facilitate simulation and design of these reactors new and more precise data are needed. DANCE is a major contributor of such data using the actinide materials and handling capabilities available at Los Alamos.

Time projection chamber

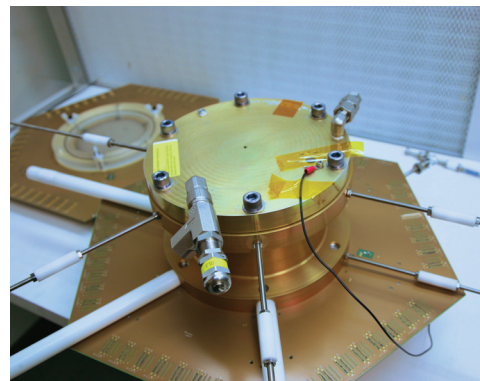
A more accurate instrument for fission studies

Precision fission cross sections are required for Defense and Nuclear Energy program needs to provide high-fidelity simulations. Until recently, the best experiments used ionization chambers to measure fission cross-section data. A drawback to these chambers is that fission events and alpha decay (from the decay of the actinide fission material) are difficult to separate accurately at the required 1% level of accuracy. A new detector is now available that overcomes the limitations of fission chambers, and that will allow both higher accuracy and more detailed studies of fission as well as address many sources of measurement uncertainty.

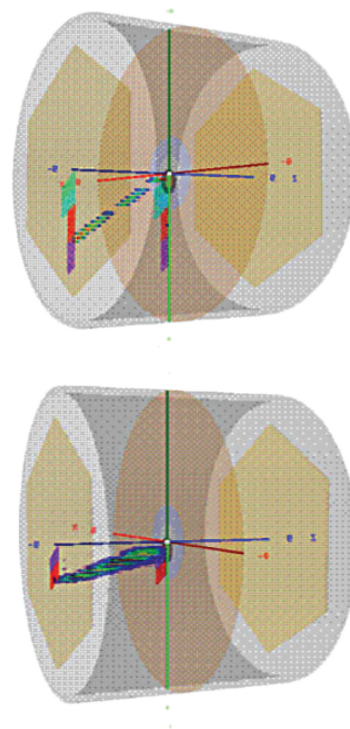
The time projection chamber (TPC) is a device originally developed for high-energy particle physics experiments to allow the tracking and measurement of many charged particles emitted in a reaction by reading out the ionization trails in a gas chamber. By tracking the trails in both space and time, a three-dimensional reconstruction of these tracks is possible. This allows identification of the particles and their energy. Because of the high energies used, TPCs for particle physics can be 2 meters in diameter or larger. For fission measurements the TPC can be scaled down to about one-tenth this size. Advances in electronics and clever design enable fabrication of a fission TPC for a fraction of the cost of the original TPCs used in high-energy physics experiments. Such a fission TPC is being collaboratively built and operated by staff from Lawrence Livermore National Laboratory and faculty and students from several universities. Initial testing in LANSCE's energetic neutron beam has shown that the design works well at detecting both light charged particles as well as heavy, highly ionizing fission fragments. The fission TPC is expected to have all 6,000 detection channels operational in 2013.

The advantage of TPCs over previously used ionization chambers and other detectors is that it allows separation of the fission signals at low energies to be distinguished from other signals, thus reducing the uncertainties in determining fission cross sections from the data. Using the fission TPCs with the LANSCE neutron beams provides measurement capabilities spanning the entire incident neutron energy range of interest for fission applications. In August 2011, the first 192 of 6,000 channels of a fission TPC were successfully demonstrated in the LANSCE high-energy neutron beam. Examples of ionization tracks from light and heavy charged particles are shown at right. When this multi-year measurement project is complete, the resulting sub-1% precision fission cross sections will provide input to the evaluation process and resulting libraries to attain a new level of precision and understanding from simulation and modeling of nuclear weapons and reactors. This project is funded by the DOE Office of Nuclear Energy under the Fuel Cycle Research and Development program and by the DOE NNSA Defense Program Science Campaigns.

By tracking charged particles in both time and space, the time projection chamber allows improved accuracy in fission cross-section determination.



Above, the TPC ionization chamber, which contains low-pressure gas and read-out detectors. Below, an example of the ionization tracks from light and heavy charged particles.



Isotope Production Facility

Radioisotopes for science, medicine, and national security

Los Alamos has a long history of producing radioisotopes for applications in medicine, biology, nuclear physics, and national security. From 1974 to 1998, isotopes were produced at Area A at the end of the beam line at what was then the Los Alamos Meson Physics Facility, now LANSCE. The isotopes were produced via spallation using the available 800-MeV proton beam.

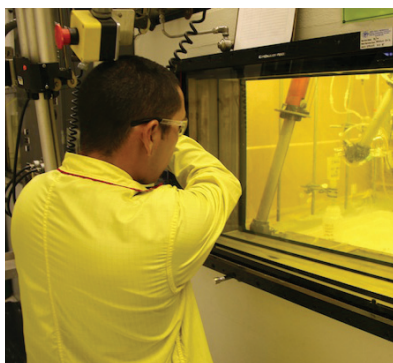
The mission for the accelerator facility changed in the 1990s and enabled the Los Alamos radioisotope program to upgrade its capabilities. Los Alamos isotopes are now produced at the 100-MeV Isotope Production Facility (IPF) at LANSCE. The IPF beam line diverges from the main LANSCE accelerator at the transition region between the 100-MeV drift tube accelerator section and the 800-MeV side-coupled accelerator section. A pulsed (kicker) magnet was installed in the transition region so that a portion of the beam can be used without impacting beam delivery to other experiments. This allows a high-intensity (up to 250 microampere) proton beam with a nominal energy of 100 MeV to be delivered to the IPF for radioisotope production.

The radioisotope production facility consists of two levels: an underground level housing the beam line and target systems, and an upper level with an equipment room and a hot cell. Targets are loaded and retrieved through the hot cell using special remote handling equipment. This makes it possible to insert and remove targets without entering the beam tunnel or otherwise impacting accelerator operations. The target station allows for irradiation of several targets simultaneously, each at its own energy range.

IPF was commissioned in 2004 at the cost of \$24 million and has been instrumental in providing critical isotopes like strontium-82—used for cardiac imaging with positron emission tomography (PET)), and germanium-68—used as a calibration source for PET instruments, to a variety of domestic and international customers. During IPF's manufacturing cycle, strontium-82 produced here is estimated to reach more than 23,000 cardiac patients each month.

The IPF mission recently moved from the DOE Office of Nuclear Energy to the Office of Science, Office of Nuclear Physics. Coupled with this move is the expectation that IPF will be instrumental in the development of new research and development projects focused on new isotope lines, novel isotope production methods, and the generation of data and expertise to support the isotopes and nuclear physics communities.

In line with these new expectations, the Laboratory's isotope team recently partnered with LANSCE scientists to develop cross-section data for the novel accelerator-based production of actinium-225. This isotope has shown significant promise as a cancer therapeutic. IPF and Weapons Neutron Research staff developed experiments to provide important yield data for production of the potential therapeutic isotopes actinium-225, radium-225, and actinium-227. These data will be used to develop a proton-production profile for actinium-225 that will be key in determining the value of accelerator-produced material at IPF, Brookhaven National Laboratory's Linear Isotope Producer, and the future LANSCE Materials Test Station facility. Early estimates indicate that the Materials Test Station could match current domestic annual domestic supply in 1-3 days of operation.



New isotope lines, novel production methods, and the generation of data and expertise supporting the isotope and nuclear physics communities are planned.

At left, using remote manipulators, a Los Alamos researcher handles target discs containing newly formed radioactive isotopes. At right, a target assembly used to produce the raw materials for radioisotopes.

Proton radiography

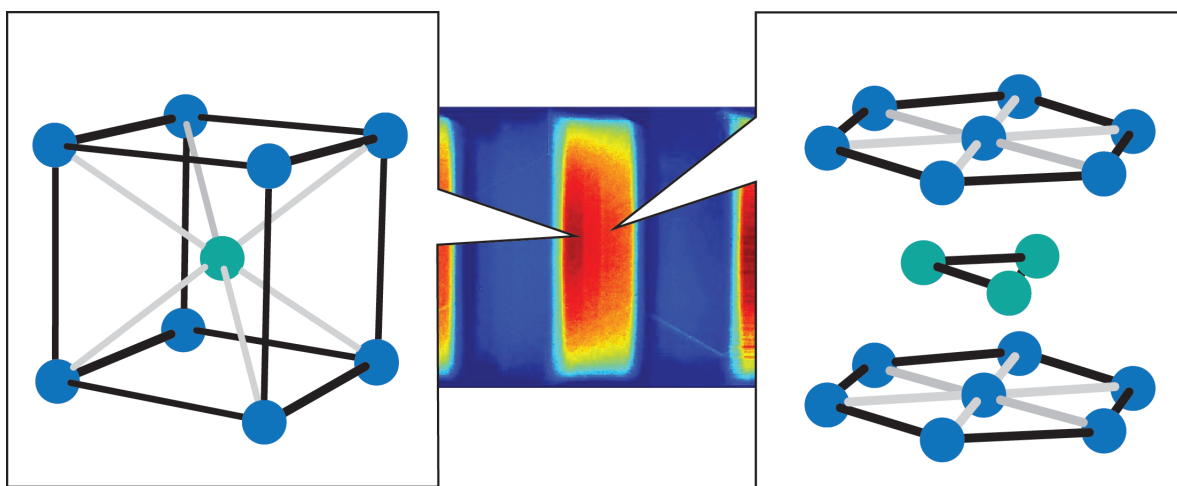
Providing a window into phase transition

One of the uses of proton radiography is to interrogate dynamic materials properties of interest to the weapons program. One such property is how materials undergo phase transitions when subjected to high-pressure shock waves. Phase transitions occur as a result of external conditions, mostly as a change in temperature, pressure, or both. For example, the phase transitions of water are familiar to all. As the temperature drops below freezing, water undergoes a phase transition from a liquid to a solid. Some phase transitions occur when crystal structure changes from one lattice formation into another. This is an example of a solid-solid phase transition. One well-studied solid-solid phase transition that we use to understand phase transitions in other materials of interest to the weapons physics community is one that exists in iron. This phase transition is solid-solid, consisting of a rearrangement of the spatial distribution of atoms. This results in a change of the material density by approximately 12%, as the atoms become more closely packed. This can be compared to the 4% change in density that occurs when ice melts into water.

Using the pRad facility (for details, please see page 12) at LANSCE, researchers have studied this solid-solid phase transition in iron by applying dynamic high pressure to samples and taking “freeze-frame” radiographs as the medium

is being transformed. A 40-millimeter bore powder gun was coupled to the pRad beam line and imaging system, and the impact of the projectile on the target sample was synchronized to the proton beam pattern. One of the advantages of using proton radiography for these experiments is that in situ measurements of the shape, velocity, and density changes of the waves in the bulk of the sample are achieved, instead of inferring these properties by extracting their effects on surface diagnostics.

When a compressed material changes phase it doesn't do so instantly. Instead, it transitions through a mixed phase as it transforms to the end-state phase for a given pressure, volume, and temperature. In the case where compression has been slowly applied and held for a long time, common phase diagrams show the phase boundaries as sharp lines. When the compression is applied with high strain rate, however, the phase boundaries are no longer crisp as the kinetic effects of the crystal reorientation delay the transitions, resulting in regions of mixed phase. The techniques demonstrated in work so far will next be used to examine dynamics of these regions. This work is supported by NNSA Science Campaigns.



Radiograph shows the front of the shock wave followed by a transition in the phase of the iron from the less dense cubic structure to the hexagonal structure.

With proton radiography, in situ measurements of the shape, velocity, and density changes of the waves in the bulk of the sample are possible.

Studying high-speed surface dynamics using the Los Alamos proton radiography capability

When a shock wave traveling in a metal reaches the surface, material can be ejected from the surface and travel at high velocity. Los Alamos uses proton radiography to capture multi-time data to inform ejecta production and transport models.

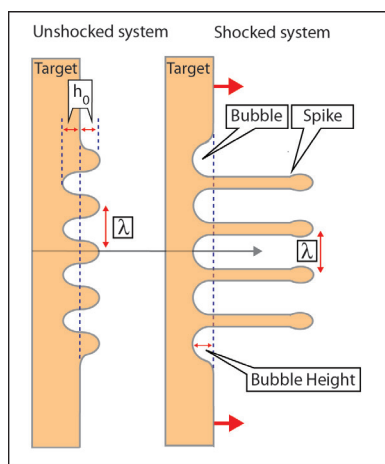
The Laboratory is presently engaged in the development and implementation of ejecta source and transport models for integration into Los Alamos hydrodynamic computer codes. The underlying idea proposed is that ejecta are produced by the Richtmyer-Meshkov (R-M) instability, which occurs when a strong shock passes through an interface between two regions of different density. When a strong shock strikes a water-air interface, the “troughs” of the waves, where the shock wave hits first, start to grow above the “crests.” The R-M instability is much less well understood when interfaces are solid-gas or solid-vacuum. Los Alamos is conducting experiments to develop and validate models for ejecta production and transport by creating strong shocks in metals using high explosives (HE) and using proton radiography to examine the evolution of the metal-vacuum interface.

To create the conditions of interest, Laboratory scientists use a HE plane-wave lens configuration coupled to a metal target. The Los Alamos-developed HE lens generates a planar detonation wave that drives a planar shock into the target creating pressures of hundreds of thousands of atmospheres. In the experimental data shown below, on the

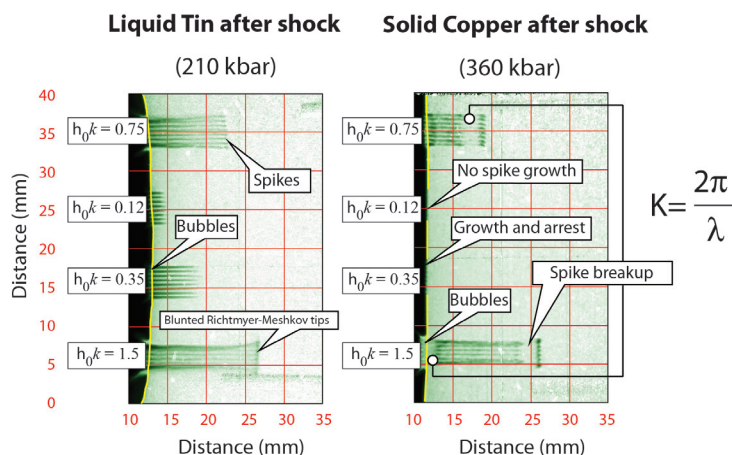
open side of the target, four bands of sinusoidal grooves are precisely machined into the surface. The amplitude (how tall the grooves are) divided by the wavelength (the distance between wave crests) is an important scaling quantity in R-M theory. For their experiments, wavelengths and amplitudes have been chosen to match the resolution capability of the Los Alamos pRad facility using the X3 magnifier. In the experiments using tin as the target material, the researchers produce shocks of sufficient strength that the tin liquefies and, as result, the material strength does not play a role in the growth of the grooves. In the experiments using copper as the target material, the material remains solid with the strength of the solid modifying how the material responds.

The unique multi-frame, high-resolution, penetrating imaging capability of the pRad facility allows tracking of the growth and evolution the instability as a function of time. Additionally, scientists also measure the surface velocity with Doppler velocimetry. From the measured free surface velocities, they are able to determine the shock strength, which is several hundred thousands of atmospheres of pressure.

Data from these experiments are used by Laboratory scientists to develop and validate a physics-based ejecta model that will be incorporated into the Laboratory’s hydrodynamic computer codes. This work is supported by NNSA Science Campaigns.



As the shock travels through the target it reaches the “troughs” of the grooves first and, as a result, these “troughs” invert to form the spikes that grow and travel away from the surface. The groove “crests” lag behind the free surface and essentially feed material into the spikes. In R-M theory these are termed “bubbles.”

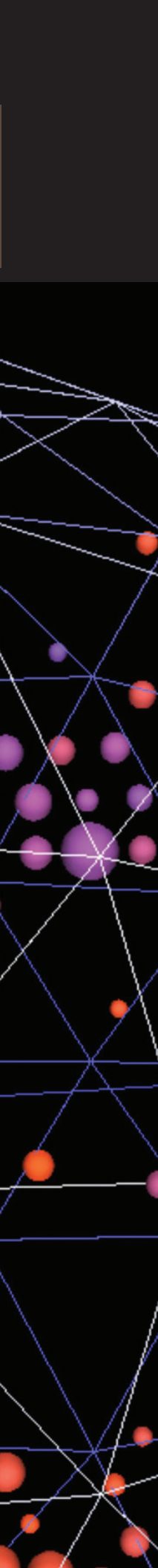


Proton radiography images from two experiments showing the time evolution of the spikes and bubbles approximately 8 microseconds after the shock has reached the surface of the target. The spikes with the largest $h_0 k$ products grow the fastest; k is the ratio of 2π divided by the wavelength λ .

Nuclear and particle physics

The Standard Model and beyond





Despite its success in describing much of particle and nuclear physics,

the Standard Model is incomplete, a fact well recognized by physicists seeking a better understanding of the nature of the universe. Employing Los Alamos's expertise in nuclear physics, particle physics, astrophysics, and cosmology, the Laboratory has undertaken refining the Standard Model as one of its grand scientific challenges. This research is supported by the DOE Office of Science, Office of Nuclear Physics and Office of High Energy Physics; the National Science Foundation; and internal Laboratory Directed Research and Development (LDRD).

In support of this endeavor, Laboratory scientists perform experiments using neutrinos and neutrons; experiments that not only further understanding of the fundamental laws of physics, but also result in applications benefiting the nation by supporting the Laboratory's national security mission.

For example, the LANSCE proton accelerator, originally designed for basic nuclear physics experiments, is used to take real-time radiographs of the explosive processes used to begin the detonation of a nuclear weapon. Particle beam and detection techniques also hold promise for the detection of smuggled nuclear weapons or their components. In addition to its extensive experimental capabilities, Los Alamos National Laboratory hosts what is arguably the most diverse nuclear theory group in the country. The group's work on nuclear structure and nuclear astrophysics, neutrino physics, quantum chromodynamics and heavy ion physics, and fundamental symmetries and physics beyond the Standard Model is well aligned with the DOE Nuclear Physics priorities and provides much needed support for the rich experimental program at Los Alamos, both fundamental and applied.

Developing a better understanding of neutrino physics

Together with photons, neutrinos are the most numerous particles of the universe; yet there is still much not known about them. We cannot see or feel these particles, although every second trillions of neutrinos pass through our bodies. Neutrinos have surprised us before, and are fertile ground in which to develop a better understanding of the Standard Model. For example, until recently, the Standard Model assumed that neutrinos were without mass. Scientists now know, however, that they have a small, but not yet measured mass.

MAJORANA and the nature of neutrinos

A key question left unanswered by the Standard Model is whether neutrinos and their anti-particles are the same or different particles. To help resolve this question, Los Alamos researchers are lending their expertise in ultrasensitive particle detection and radiation shielding to the MAJORANA DEMONSTRATOR experiment, an underground detector to be built in South Dakota. Using skills gained from a previous experiment that detected neutrinos from the sun, Los Alamos scientists will help build a sensitive detector that catches these rarely seen events. If successful, MAJORANA will lead to a much larger international experiment with even greater sensitivity.

LBNE and the matter, anti-matter imbalance

With extensive expertise in neutrino physics and an ability to manage large scientific projects, Los Alamos scientists also play a key role in the development of the proposed Long Baseline Neutrino Experiment (LBNE). LBNE may lead to a better understanding of why the universe is mostly composed of matter and why anti-matter is rare. The project, which will search for muon neutrinos transforming into electron neutrinos, uses particles produced at the Fermi National Accelerator Laboratory (Fermilab) in Illinois and detected in a "near" detector at Fermilab and a "far" detector in a South Dakota underground laboratory.

At left, a neutrino event recorded by the MiniBooNE experiment. The ring of light, registered by some of more than 1,000 light sensors inside the detector, indicates the collision of a muon neutrino with an atomic nuclei.

Beyond the Standard Model

An introduction

Developed in the 1970s, the Standard Model of particle physics describes the subatomic world through 12 elementary particles and their interactions through 3 of the 4 forces in nature. Its basic elements include the electromagnetic, strong, and weak forces, and 6 quarks (up, down, charm, strange, top, and bottom), 6 leptons (electron, electron neutrino, muon, muon neutrino, tau, and tau neutrino), and 4 force carriers (photon, gluon, and Z and W bosons).

The common constituents of matter are created by up and down quarks exchanging gluons to bind into protons (two up quarks and a down quark) and neutrons (one up quark and two down quarks). Single quarks and anti-quarks exchange gluons and bind into mesons. Protons and neutrons exchange mesons to bind into the nuclei of “normal” matter. The positively charged nucleus exchanges photons with electrons to bind into the atoms that make up the “normal” matter with which we are all familiar.

To date, the Standard Model provides a successful description of nature at energy scales ranging from atomic physics (a few electronvolts) up to collider physics (approximately 200 GeV). And while it is a well-established-and well-tested theory, it does not explain everything in the universe; for example, gravity. The theory also breaks down when it comes to explaining the nature of dark matter and energy and the imbalance of matter versus antimatter in the universe. Other aspects not fully tested concern the electroweak symmetry breaking mechanism, the masses and interactions of neutrinos, and new physics above the TeV (teraelectron volt) scale. Los Alamos scientists are studying all of these challenges in their fundamental NPAC research.

ELEMENTARY PARTICLES

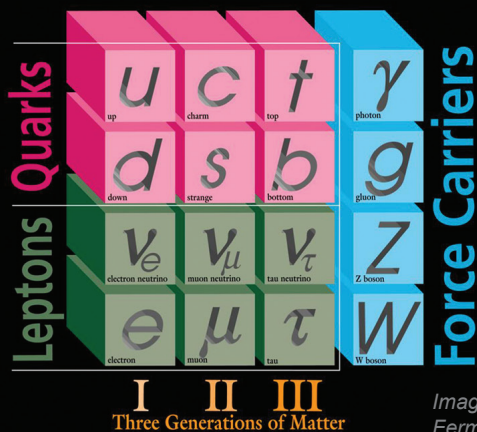


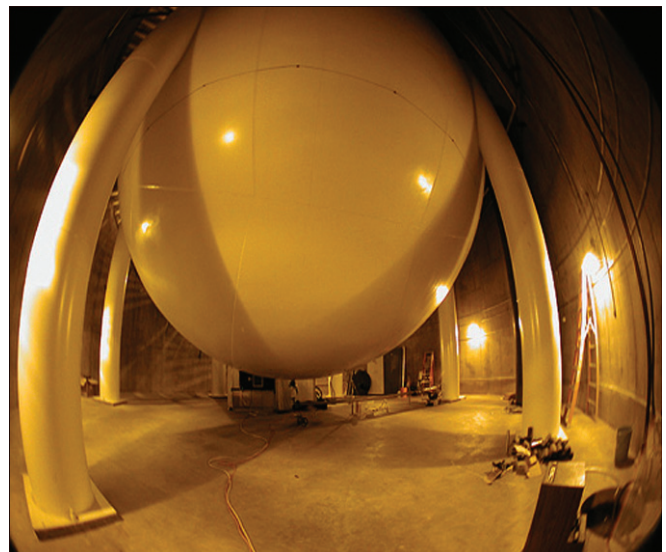
Image courtesy of
Fermilab, 95-759

MiniBooNE and short distances

Like the LBNE, MiniBooNE (for Mini Booster Neutrino Experiment) at Fermilab also searches for neutrino transformations. However, MiniBooNE does this over a much shorter distance—a half a kilometer. MiniBooNE data so far are providing intriguing hints pointing to physics beyond the Standard Model. Los Alamos scientists lead the effort to design a new generation of experiments that can resolve this mystery.

The MiniBooNE experiment starts with a beam of muon neutrinos produced by the particle accelerator at Fermilab and then detects electron neutrinos a half kilometer away. The number of electron neutrinos detected is larger than predicted by calculations based on the Standard Model, suggesting that some of the muon neutrinos are changing into electron neutrinos in flight. While this phenomena is known to occur over longer distances, its observation at this short distance suggests new physics is at work. One possible explanation is a fourth, as yet undiscovered neutrino that would be considered “sterile,” since it wouldn’t interact with normal matter at all.

The Laboratory’s role in the MAJORANA, LBNE, and MiniBooNE projects support an institutional NPAC goal of discovering new science beyond the Standard Model.



Located deep underground to shield the sensitive physics experiment from cosmic background radiation, the MiniBooNE detector at the Fermi National Accelerator Laboratory is an 800-ton sphere designed to search for neutrino oscillations.

Expanding knowledge of fundamental neutron physics

In the next decade, a wide array of experiments will examine fundamental neutron physics and thus will help refine understanding of the Standard Model.

The neutron makes an ideal laboratory for studying new ideas in particle physics because its properties can be measured precisely and it is simple enough to accurately calculate Standard Model predictions. Looking for differences between the measured and predicted properties provides a means to measure physics at the very high energy scales that cannot be probed directly.

Our experimental program is designed to address the highest priorities identified by the Nuclear Science Advisory Committee and supported by the DOE Office of Science, Office of Nuclear Physics and to enable our strategic goal of planning and marketing a world-class, intermediate-scale nuclear physics facility at Los Alamos.

Ultracold neutron research at Los Alamos

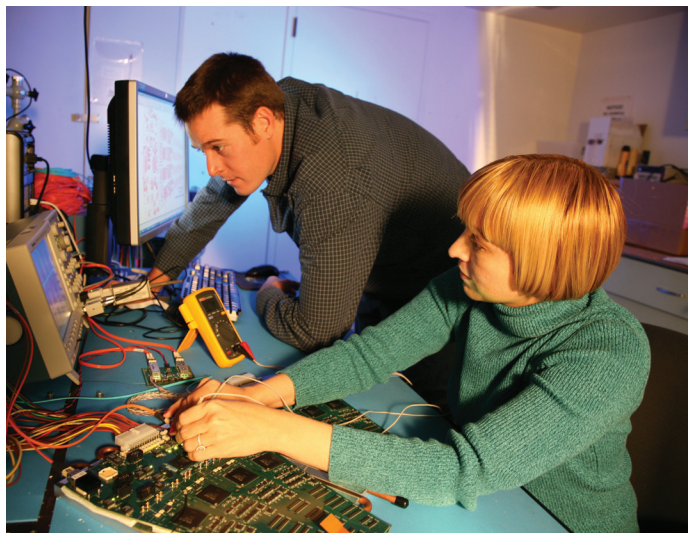
In this context, precision measurements of neutron properties offer great opportunities to probe new physics, and Los Alamos's ultracold neutron team plays a leading role worldwide in exploiting the unique properties of ultracold neutrons.

Ultracold neutrons are neutrons moving so slowly (less than 7 meters a second) that they can be contained by magnet fields, special materials, and even gravity. The ability to trap these neutrons allows more time for precise measurement of their properties. In addition, because they can be transported by special pipes, the measurement can take place far away from where they are produced, greatly reducing backgrounds created in the production process. Ultracold neutrons are produced at Los Alamos National Laboratory by allowing higher-energy neutrons to interact with solid deuterium at low temperatures. The neutrons interact with the deuterium crystal in such a way that they lose almost all of their energy. Los Alamos scientists pioneered this method of producing ultracold neutrons, which is more efficient than previous techniques.

The Ultracold Neutron Source is essential to advances in neutron experiments such as precisely measuring the neutron lifetime and other parameters of neutron decay. Improvements in these areas will inaugurate a new class of precision neutron decay experiments, enabled by the unique features of the Los Alamos Ultracold Neutron Source: a high density of ultracold neutrons with the world's highest degree of polarization, low background

from the spallation source, and our previously developed large area silicon detectors. Simultaneously with the experimental effort, we will carry out a theoretical program to elucidate the implications of the measurements.

For more details on ultracold neutron studies at Los Alamos, please see pages 23 and 24.



Los Alamos National Laboratory researchers test components of a new detector for PHENIX, an experiment at Brookhaven National Laboratory that seeks to better understand quantum chromodynamics.

nEDM

The discovery of a non-zero electric dipole moment of the neutron would be a physics breakthrough and could explain why the universe is almost completely made of matter, instead of antimatter.

To that end, the Neutron Electric Dipole Moment (nEDM) project will look for a tiny separation of positive and negative charges inside the neutron by creating ultracold neutrons in a bath of superfluid liquid helium at a temperature less than 1 degree above absolute zero. The experiment will be so precise that if the neutron were actually the size of the earth, a charge separation of only 3 millionths of a centimeter would be detectable.

The quest to define quantum chromodynamics

Quantum chromodynamics (QCD), the theory of the strong nuclear force—proposed in the 1970s and now well established—describes one of the fundamental forces in nature in terms of its point-like degrees of freedom, quarks, and gluons. Although part of the Standard Model, QCD is so

complicated researchers can't yet predict in many cases what happens in nature. Confined in composite states, a quark or gluon can never be observed in isolation. Yet when probed at high enough energy scales, they are observed to behave as nearly free particles. Scientists still have a great deal to learn about the internal structure of QCD bound systems; of protons and neutrons, collectively called nucleons, and how their inner workings may change when they are bound together as nuclei.

PHENIX

Los Alamos physicists are actively involved in studying a variety of QCD matter—proton and nuclear structure as well as quarks and gluons freed from their confines through the creation of quark-gluon plasma.

PHENIX (short for Pioneering High Energy Nuclear Interaction eXperiment) at Brookhaven National Laboratory's Relativistic Heavy Ion Collider (RHIC) is the focal point for the group's work in QCD. RHIC is the most versatile collider in the world, with the ability to collide heavy nuclei over a wide range of energies extending up to 200-gigaelectron volts (GeV) center-of-mass energy per nucleon in each collision, and also light nuclear species on heavy ones. RHIC is also the world's first and only collider of high-energy polarized protons, with the maximum proton-proton energy reaching 510 GeV.

The PHENIX team at Los Alamos is one of few groups participating in the 500-person experiment that takes full advantage of the accelerator's versatility, investigating the spin structure of the proton, the structure of "cold" nuclear matter, and the extremely hot and dense QCD matter produced in the heavy ion collisions at RHIC. As experts at designing and constructing the large particle detectors needed for this experiment, Los Alamos scientists are performing a major upgrade of a key part of the PHENIX detector.

SeaQuest

Curiously, the most common example of QCD in nature, the proton, is also the most complicated and the least under-

stood. The SeaQuest experiment at Fermilab studies the internal structure of the proton using a 120-GeV proton beam impinging upon a variety of fixed targets, at significantly lower energy than those typically run at RHIC, thus allowing the exploration of a different kinematic region. SeaQuest offers excellent opportunities to study the antiquarks ("sea quarks") in nucleons and nuclei. Los Alamos scientists led the first version of this experiment and play a leading role in the current, more advanced version.

A complementary technique for studying the internal structure of protons and neutrons is to use the electron beam at Virginia's Thomas Jefferson National Accelerator Facility to take a snapshot of the quarks and antiquarks inside the proton. There, Los Alamos recently led one experiment that studied the spin structure of polarized neutrons in ^3He , which is approximately the same as a single polarized neutron.

The benefits of basic research

Proton radiography

Invented at Los Alamos National Laboratory, proton radiography employs a high-energy proton beam to image the properties and behavior of materials driven by high explosives. The penetrating power of high-energy protons, like that of x-rays, makes them an excellent probe of a wide range of materials under extreme pressures, strains, and strain rates. The charge of the particles both affects scattering in interesting ways and allows them to be imaged with magnetic optics that gives them unique advantages for penetrating radiography. The incredible efficacy and versatility of proton radiography also stems from the ability to produce multiple proton pulses in an accelerator coupled with multiple optical viewing systems that can result in more than 40-frame movies.

The invention of imaging proton radiography is the direct result of the collaboration between the Laboratory's defense mission and basic science research scientists and supports the Laboratory's national security science mission as

The pRad facility at LANSCE. Los Alamos has used high-energy protons as a probe in flash radiography for a decade.



well as provides for fundamental science discoveries. This new capability has revolutionized dynamic materials science at Los Alamos, providing a new window for the study of shock physics, materials damage, and high explosives science. The proton radiography capability is primarily supported by the NNSA Science Campaigns, with additional support provided by other external sponsors. To read more about the pRad facility and its role in the weapons program, please see page 12.

Active interrogation

To aid in the reliable detection of smuggled nuclear weapons or weapons-grade nuclear materials, a critical need for U.S. national security, Los Alamos is focusing on using protons and muons to penetrate concealments, stimulate characteristic nuclear emissions, and detect nuclear materials. Goals include determining potential characteristic signatures, suitable detectors for those signatures, and methods for generating portable sources of interrogation beams that would facilitate offshore detection of smuggled nuclear threats. This research has been supported by the Defense Threat Reduction Agency (DTRA).

Using the LANSCE 800-MeV proton beam in experiments to identify and characterize these distinctive emissions, Los Alamos scientists have measured the yields of neutrons and gamma rays from proton pulses interacting with shielded and unshielded materials, including special nuclear materials that could be used to make nuclear weapons, which may be concealed in a shipping container. Characteristic time and energy spectra for background and target emissions following an interrogation pulse have been measured.

Computational nuclear physics

Computational nuclear physics bridges the gap between what we can observe directly in the laboratory and critical questions in physics beyond the Standard Model, nuclear astrophysics, and applications. For example, nuclear theory and simulations are critical to tying laboratory measurements to the properties of neutron stars and supernovae. Los Alamos is the lead institution in the SCIDAC-3 NUCLEI project, a collaboration of leading nuclear physicists, mathematicians, and computer scientists from eight universities and six national labs to develop the next generations of theory and computations advancing our understanding of nuclear structure and reactions. The NUCLEI collaboration uses large-scale simulations to advance our understanding of fusion and fission, and the properties of nuclear matter and neutrinos in neutron stars and supernovae.

The Ultracold Neutron Source

Discovering new physics
using a sophisticated new tool

Historically, ultracold neutrons have been inefficiently produced by starting with a huge number of room-temperature neutrons, such as in a nuclear reactor, then only keeping the very lowest energy tail.

In a more sophisticated technique developed at Los Alamos, the Ultracold Neutron Source at LANSCE makes use of the solid-state interactions between thermal neutrons and a cryogenic converter material-solid deuterium to produce more ultracold neutrons than expected, thus being known as a super-thermal ultracold neutron source.

The neutrons are released by the LANSCE proton beam striking a tungsten spallation target, with the spray of emitted fast neutrons reflected and slowed by a beryllium reflector, then further slowed by a layer of polyethylene beads at a temperature of almost -400°F. Finally, they enter a solid deuterium volume in which some of the neutrons are converted to ultracold neutron energy. These ultracold neutrons are trapped by a pipe, coated with a special isotope of nickel, and transported from the proton beam through a thick steel and concrete shield stack to the experimental floor. There, they can be piped to different experiments, including the Ultracold Neutron Asymmetry (UCNA) experiment and a test port, which can service many different user experiments. The test port's first user experiment was an engineering experiment for the neutron electric dipole moment experiment, developed at Los Alamos.

The "little b" apparatus designed to measure the total energy associated with the decay of the neutron at the UCN facility.



Ultracold neutrons

A versatile tool for probing a fundamental force of nature

Los Alamos researchers, using the power and flexibility of the Laboratory's Ultracold Neutron Source, are conducting an experiment that is providing new and undiscovered details of the weak nuclear force, one of the four fundamental forces of nature.

With an average lifetime of about 15 minutes, a decaying neutron emits a proton, an electron, and an anti-neutrino. This decay process is governed by the weak nuclear force. A property of the weak force is that an experiment can yield different results if performed in a mirror-reversed version of itself. One result of this property is that there is a correlation between the momentum of the emitted electron from neutron decay and the spin angular momentum vector of the decaying neutron. Many nuclear processes, such as the rate of fusion reactions in the sun, depend upon the precise value of this correlation. Because neutrons are both chargeless and short-lived, measuring this value, known as the A coefficient, has proved difficult.

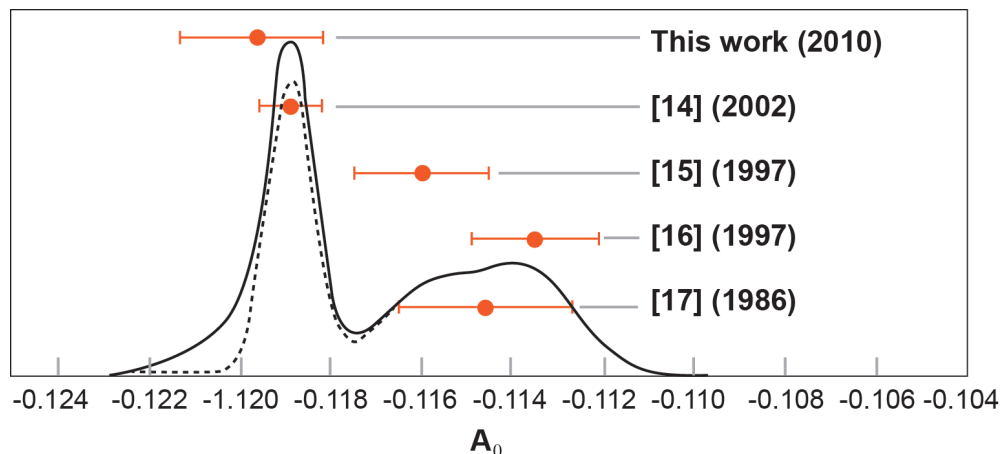
The UCNA experiment, now being conducted at LANSCE, aims to measure the A coefficient better than any previous experiment. Any A-coefficient measurement follows the same principles: neutrons are polarized (that is, all the neutron spins are aligned the same direction), then placed

in a magnetic field. When a neutron decays in the field, the emitted electron is trapped by the magnetic field and transported to one of two detectors. By counting the difference in the number of detected electrons emitted towards the spin of the neutrons and against it, the A coefficient can be extracted.

Previous experiments have all used beams of cold neutrons as their source of decaying neutrons. These experiments have been limited by two effects: the difficulty in polarizing cold neutrons to a high level and accurately measuring that polarization; and second, only a fraction of the cold neutron beam passing through the experiment volume decays, while the rest cause irreducible backgrounds in the experiment's detectors.

The UCNA experiment improves on both of these limitations by using instead ultracold neutrons as its supply. Operating at LANSCE for 5 years, the experiment has recently published a measurement of the A coefficient, competitive with the world's most precise, that has had a significant impact on the world average value. In the next few years, the UCNA team plans to push beyond the competition and make the world's most precise measurement of the A coefficient.

Using ultracold neutrons as its supply, the UCNA experiment, now being conducted at LANSCE, aims to measure the A coefficient better than any previous experiment.



The latest published result from the Los Alamos electron asymmetry experiment using ultracold neutrons, compared to previous measurements using cold neutrons. The newer results are consistent with a more negative value of A_0 due to a better control of systematic errors.

Forward silicon vertex detectors

Opening the door to new high-energy physics studies

Using its multidisciplinary expertise in large and complex projects, Los Alamos recently led the effort to construct two forward silicon vertex detectors (FVTX) for the PHENIX experiment, a collection of detectors designed to discover a new state of matter, quark-gluon plasma.

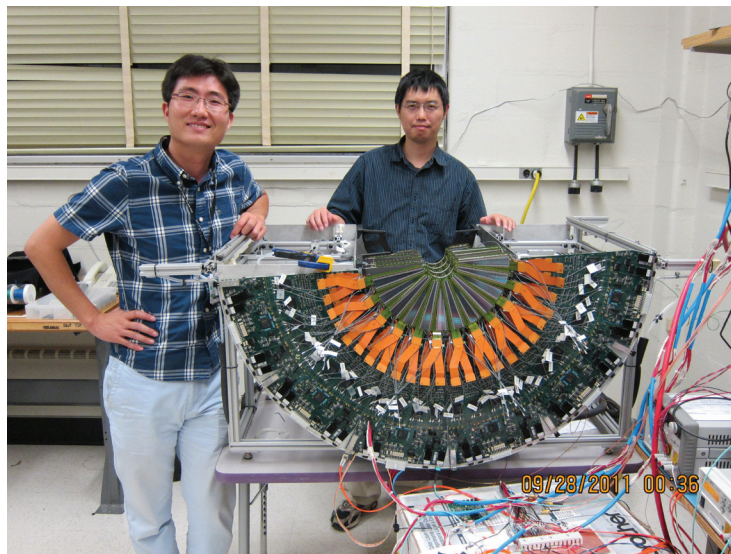
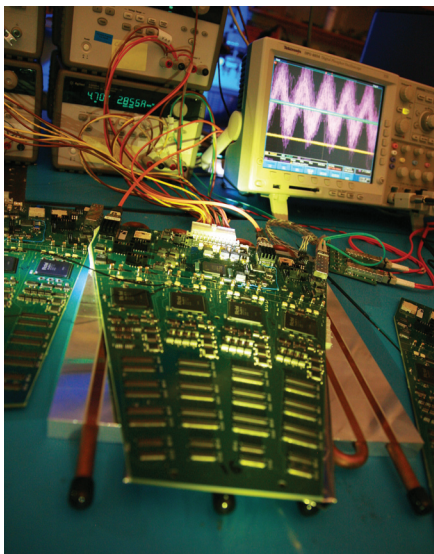
By directly identifying and distinguishing heavy quark charm and beauty decays within the acceptance of the PHENIX muon spectrometers, the FVTX will allow qualitatively new measurements of the quark-gluon plasma.

For the FVTX, the Laboratory's role included using its extensive project management expertise, as well as leading the silicon sensor, sensor readout chip, electronics readout, and mechanical designs. The detector completed its third year of construction and was installed in the PHENIX detector at Brookhaven National Laboratory in 2011, with first data collected in the spring of 2012.

The FVTX is constructed with 384 custom-designed silicon strip detectors comprising more than 1 million independent sensor channels. The strips are patterned on a 75-micron pitch, which provides precise spatial resolution, allowing an accurate measurement of the track trajectory as it exits the collision area. With this, particles produced at the point of interaction can be separated from heavy quark mesons, which travel a short distance from the interaction point and then decay into other particles. The readout of the 1 million channels of silicon is performed by electronics designed by Los Alamos that suppress hits below threshold in real time and transfer the data over hundreds of high-speed fiber optic links, allowing all the data to be read out in the short time between nucleus-nucleus collisions.

The detector construction was supported by the DOE Office of Science, Office of Nuclear Physics. The work supports Los Alamos's goal of establishing the next major scientific thrust at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory.


For the FVTX, the Laboratory's role included using its extensive project management expertise, as well as leading the silicon sensor, sensor readout chip, electronics readout, and mechanical designs.



A custom detector electronics card (left), and the mechanical model for a full half-arm, which is comprised of four half-disks (right).

Astrophysics and cosmology

Exploring the explosive universe



Gamma-ray bursts are common, yet random, and fleeting events that have mystified astronomers since their discovery in the late 1960s. Many scientists say longer bursts (more than 4 seconds in duration) are caused by massive star explosions; shorter bursts (less than 2 seconds in duration) are caused by mergers of binary systems with black holes or neutron stars. While uncertainty remains, most scientists say in either scenario a new black hole is born.

(Illustration: NASA/D. Berry)

For first-generation scientists like Robert Oppenheimer and

Hans Bethe—who studied the stability of degenerate stars and energy production in stars, respectively—through to the current generation of Los Alamos scientists, astrophysics and cosmology have posed questions that stimulate intellectual curiosity and hone the skills needed to address the Laboratory’s goals and mission. The primary mission of Los Alamos has always been the development of nuclear weapons and the maintenance of the stockpile. Achieving an understanding of nuclear reactions, radiation transport, and equations of state in stars has helped weapons designers to better understand nuclear explosions and to verify the bomb codes. In the current era of stockpile stewardship without actual testing, the exciting problems posed by astrophysics and cosmology are providing an important test-bed for developing high-performance computing techniques; modeling complex systems over wide dynamic ranges; verifying essential programmatic codes; and developing techniques for the quantification of margins and uncertainties needed to address key national needs.

Since the signing of the Limited Test Ban Treaty in the early 1960s, another important part of the Laboratory’s mission has been to help monitor and reduce the threats posed to our nation by the advanced technology of others. The initial impetus provided by the need to monitor Soviet compliance with the Test Ban Treaty led to Los Alamos’s first space missions—called the Vela satellites—which carried gamma-ray, x-ray, and energetic particle detectors into space. While demonstrating the world’s first persistent global nuclear monitoring capability and acting as a deterrent to Soviet atmospheric nuclear testing, those satellites also enabled the discovery of previously unimagined extreme astrophysical phenomena like gamma-ray bursts, soft gamma-ray repeaters, and x-ray bursts. The chance to participate in those exciting astrophysical discoveries attracted top scientists with significant talent that, in turn, expanded into Los Alamos’s current important role in our nation’s threat monitoring systems and leadership for space-based missions in the DOE complex. This healthy synergy between open astrophysics and classified programmatic work continues today. To give just one example: the effort at Los Alamos that led to the successful development of the on-board, real-time software for triggering on and spatially localizing gamma-ray bursts for the NASA’s Swift satellite helped develop techniques and concepts that are now applied to nuclear explosion monitoring.

Los Alamos technical staff members who identify themselves as astrophysicists provide the Laboratory considerable strength in computational methods, computer/database architectures, code validation, data analysis, and weapons physics—areas of expertise that are essential for pursuing the nuclear weapons

Computational assets

Tools and expertise combine for groundbreaking modeling and simulations

Computational astrophysics leverages both the high-performance computing capabilities and computational physics expertise at Los Alamos National Laboratory. The Laboratory's Advanced Simulation and Computing (ASC) program developed the first petascale computer and has retooled old supercomputers into data mining machines. The computing power has allowed Los Alamos to undertake groundbreaking simulations in all aspects of astronomy. On top of this, the ASC expertise in computational physics produces many physics tools ideally suited to solving astrophysics problems.

The close connection between the ASC program at NNSA and computational astrophysics allows exciting gains in both programs. Simulations of supernova explosions demonstrate this symbiotic collaboration. Los Alamos astrophysicists have tapped expertise within the ASC program in turbulence, nuclear reaction physics, atomic physics, and radiation-hydrodynamics to conduct detailed computational simulations of supernova explosions and their observational diagnostics. These diagnostics (full spectra, luminosity versus time) are then directly compared to current and upcoming astrophysical missions led by the National Science Foundation or NASA and Los Alamos: Large Synoptic Survey Telescope, Palomar Transient Factory, Swift, James Webb Space Telescope, Wide-Field Infrared Survey Telescope, Nuclear Spectroscopic Telescope Array. Los Alamos has joined many of the scientific teams on these missions.

Astrophysics provides a recruitment and training opportunity for young scientists coming into the ASC program, but the relationship moves beyond this level. Software developed for astrophysics analyses has been retooled to help in the ASC program. This software now plays an important role in the above-ground experiment community at the Laboratory.

mission. They also offer extensive experience with autonomous robotic instrumentation, real-time knowledge extraction, and machine learning; and have developed new methodologies that are essential for pursuing the threat reduction mission.

Astrophysics and cosmology research also fosters active participation in the broader scientific and technical community beyond the Laboratory, and by leveraging Los Alamos expertise and capabilities has enabled the development of strategic collaborations with academia, industry, and other national laboratories. With nearly 100 scientists participating at some level in astrophysics or cosmology research at Los Alamos, the scope of the Laboratory's research is broad and touches essentially all areas of active research.

The work in this field produces groundbreaking science, significant national security programmatic contributions, and fosters and demonstrates major scientific and technical capabilities, one of the Laboratory's NPAC goals. Major sponsors for this research are the Laboratory's discretionary research and development funding, NASA, DOE Office of Science, and other government organizations.

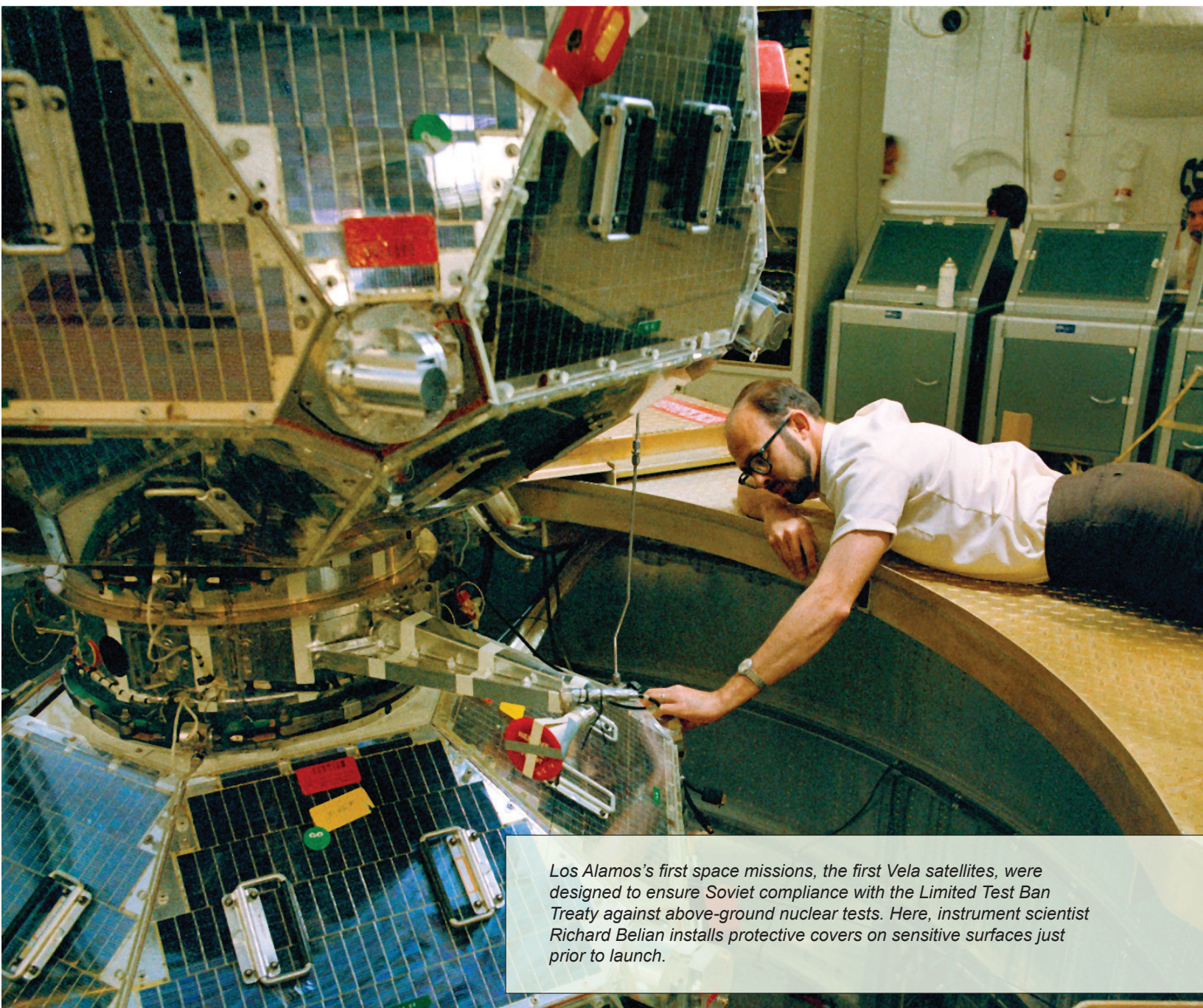
Precision cosmology

Cosmology has emerged over the last two decades as a precision science, having progressed impressively to the current level of measurement accuracy of ~10%, with sub-percent accuracy targeted for the near future. This remarkable improvement presents an extraordinary challenge for modeling and theory: predictions must be made to at least the same level of accuracy, and preferably better.

By leveraging approaches and resources of the Advanced Simulation and Computing program (ASC), Los Alamos scientists are conducting state-of-the-art numerical simulations of the universe. One recent highlight is the introduction of a new quantification of margins and uncertainties (QMU) framework—originally developed as part of the ASC program—to cosmology, a new approach termed “cosmic calibration.” This framework allows accurate parameter constraints to be obtained from combining observations with a small number of costly, high-performance cosmology simulations. This precision calibration approach promises to be a powerful technique for both designing and interpreting the measurements from the next generation of massive sky surveys like that which will be conducted by the Large Synoptic Survey Telescope. Those astronomical surveys are designed to explore the signatures of dark energy and dark matter—in other words, physics “beyond the Standard Model.”



A simulated supernova explosion.



Los Alamos's first space missions, the first Vela satellites, were designed to ensure Soviet compliance with the Limited Test Ban Treaty against above-ground nuclear tests. Here, instrument scientist Richard Belian installs protective covers on sensitive surfaces just prior to launch.

Nuclear astrophysics

Theoretical work on nuclear astrophysics at Los Alamos has made key contributions to understanding core collapse supernova, gamma-ray bursts, and nucleosynthesis; and neutron structure, and cooling and bursting behavior. Los Alamos has developed a cutting-edge astrophysics effort in modeling the hydrodynamic and transport aspects of a wide class of explosive astrophysical phenomena, including some of the pioneering work on core collapse supernova. These studies include detailed calculations of the progenitors, the explosive engines and observational properties of these outbursts. Los Alamos is a world leader in the calcu-

lation of nuclear and neutrino reaction rates of relevance to these phenomena. This is corroborated by the wide use of the Los Alamos-developed methods and databases to calculate nuclear structure, electron capture rates, and the neutrino cross sections in simulations of supernova, x-ray bursts, and gamma-ray bursts. Los Alamos has played an instrumental role in delineating the role of neutrino interactions and flavor transformations in extreme astrophysical environments. Los Alamos National Laboratory has pioneered the development of non-perturbative quantum Monte Carlo methods to study dense neutron-rich matter of relevance to neutron stars. In this context, Laboratory researchers also have studied the possibility of novel phase

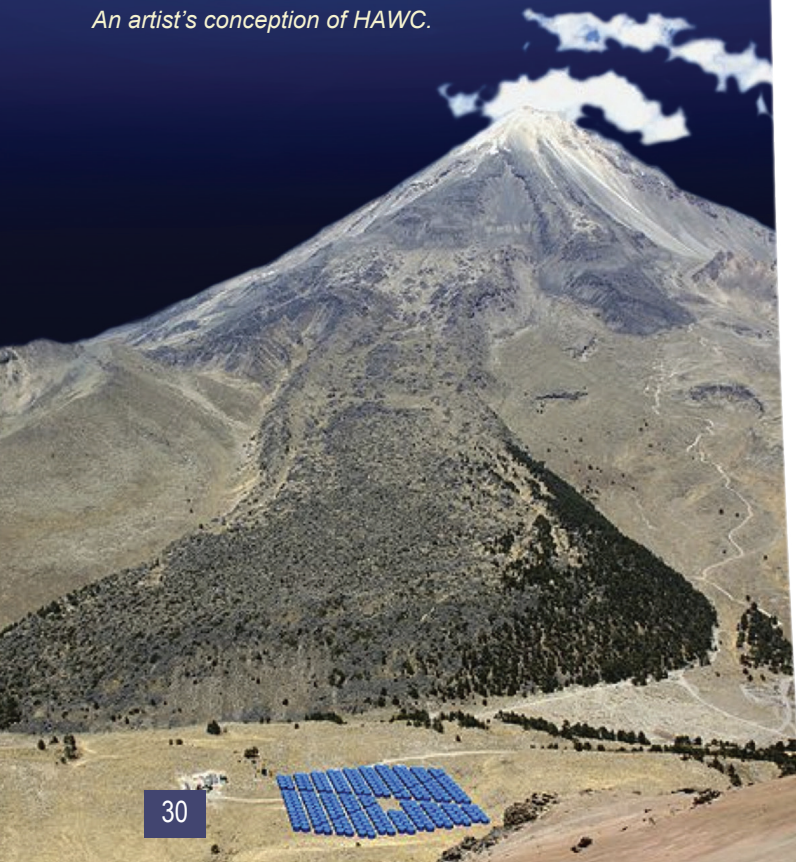
HAWC

Elevating gamma-ray observation to a new level

Building on the success of Milagro, the High-Altitude Water Cherenkov (HAWC) Gamma-Ray Observatory will be located at 13,500-foot elevation on the slopes of Mexico's Pico de Orizaba volcano. HAWC's higher elevation, as compared to Milagro's 8,700 feet, will result in more particles reaching the detector for the same energy gamma ray. While HAWC still uses water to detect gamma rays, the water will be in 300 large tanks, 7.3-meters in diameter and 4.5-meters deep, allowing the total surface area of the detector to be much larger. Also, this design of optically separated tanks will improve the ability to distinguish between source and background emissions. Detailed Monte Carlo simulations of this design show that HAWC will be able to detect sources that are 15 times weaker than could be detected with Milagro.

HAWC is being built by a collaboration of 16 U.S. universities, 14 Mexican universities, and Los Alamos National Laboratory. Construction began in spring 2011 and will be completed in 2014. The DOE Office of Science supports the Los Alamos effort.

An artist's conception of HAWC.



transitions to de-confined quark matter and have explored their consequences for neutron star structure and evolution.

Stellar astrophysics

Stellar astrophysics theory has a long tradition at Los Alamos and comprises much of the entire field, such as stellar structure and stellar evolution including stellar pulsations, stellar winds, and nucleosynthesis in stars; and compact stars like white dwarfs and neutron stars. The Laboratory has a renowned theory and observation group exploring stellar oscillations as a means to probe stellar interiors. They are also examining stellar instabilities and mass ejection by massive stars. Studies at Los Alamos of winds from massive stars complement the population synthesis studies on progenitor models for gamma-ray bursts. The stellar evolution effort ranges from low-mass stars over massive stars that make supernovae, to very massive and super-massive stars that can make big black holes. The massive stellar models that include rotation and magnetic fields are among the most comprehensive in the world, and follow the stellar evolution all the way until the center of the star becomes unstable and collapses. They also provide initial models for core collapse simulations, supernova explosion and gamma-ray burst studies, and nucleosynthesis calculations performed by Laboratory astrophysicists. An effort currently under way at Los Alamos investigates the formation of the first stars in the universe, their evolution, their explosive deaths, and their impact on their environment. The Laboratory has built up one of the world's most comprehensive efforts on this topic, including the nucleosynthesis of the first stars and ionization of the surroundings of the first stars using radiation hydrodynamic simulation coupled to reaction chemistry.

High-energy transients

Since the discovery of gamma-ray bursts and x-ray bursts by Los Alamos National Laboratory instruments aboard the Vela satellites, Los Alamos has been a leader in the study of explosive astrophysical transients. Today's premier observatory for the study of gamma-ray bursts is the Swift spacecraft. Swift employs a wide-field gamma-ray coded aperture imager to observe the sky continuously for sudden bursts of high-energy emission. When it finds a gamma-ray burst, it accurately calculates the position, notifies ground-based telescopes (like Los Alamos's RAPTOR telescopes), and autonomously slews the spacecraft to point its sensitive x-ray telescope and UV/optical telescope at the gamma-ray burst for follow-up observations. The core of this fully autonomous, rapid-response capability is high-performance, real-time transient recognition software that was written at Los

Alamos. This software has enabled high-impact discoveries that twice have generated four back-to-back papers in the journal *Nature*.

Optical transients

In recent years, robotic telescopes developed at Los Alamos have shown that bright flashes of visible light are also generated by gamma-ray bursts. This new component of optical emission from gamma-ray bursts, emitted during the critical first minutes, carries the signature of the explosion itself. This rapidly varying visible light, so-called prompt optical emission, is best understood as emission from the same internal shocks in the ultra-relativistic jet that generates the gamma-ray emission. Simultaneous observations of the prompt optical and gamma-ray emission therefore provide a powerful probe of the physics of the extreme events that generate gamma-ray bursts. The Laboratory's robotic telescopes are also providing new clues about the nature of a slower rising and decaying component of the optical emission, called the optical afterglow. For example, that work shows that the shape of the early afterglow light-curve is a tool for exploring the explosion environment and evolution of the jet/environment interaction. Since a significant number of gamma-ray bursts are expected to occur at high redshifts ($z > 5$)—when the universe was less than 10% of its current age—optical afterglow observations can probe the nurseries of the very first stars. Los Alamos's autonomous robotic telescopes are also beginning to discover new classes of previously unknown astrophysical transients. For example, the Laboratory's robotic system autonomously discovered a class of cosmic explosions in the distant universe that are bright optical emitters and have durations of tens of minutes—but that do not generate strong gamma-ray emission. Evidence is also emerging for interesting new classes of optical transients in our galaxy and in the local universe. With the discovery of bright flashes lasting less than 10 seconds from explosions at distances measured in billions of light years from Earth, the night sky has shown itself to be much more dynamic than almost anyone suspected.

Very high-energy gamma rays

Nature accelerates particles to energies exceeding 1 joule, yet these astrophysical accelerators are not understood. Observational research using a new generation of instruments is exploring the sources and acceleration mechanisms in the extreme objects that are predicted to accelerate particles to these astounding energies. These objects include massive black holes in active galactic nuclei, shocks in supernova remnants, and intense electromagnetic fields around spinning pulsars.

Fenton Hill Ideally situated for astrophysics studies

Located at a remote desert site with an elevation of 8,700 feet in the Jemez Mountains of the Santa Fe National Forest, Los Alamos National Laboratory's Fenton Hill Observatory is an ideal spot for astronomical research, instrument development, and educational outreach. The 30-acre site, located 38 kilometers west of the main Laboratory campus as the crow flies, was originally developed in the 1970s for geothermal energy research. However, since the late 1990s the primary activity at the site has been astronomical research, acting as home to the Milagro Gamma-Ray Observatory and the RAPTOR (RAPid Telescopes for Optical Response) optical telescopes (shown below). The nearby location and shielding from light pollution make it an excellent site for the development and testing of new instrumentation. Another important activity at the site has been educational outreach. For a dozen summers, Fenton Hill has been used as part of the Earth Watch Student program. Today, Fenton Hill is a hotbed for the development of autonomous, robotic telescopes, so-called thinking telescopes (please see page 35), which persistently monitor the night sky, recognize explosive astrophysical transients as well as more subtle anomalies in persistent sources, and make real-time, robotic follow-up observations without human intervention.



With a long and rich tradition of high-energy astrophysics research, Laboratory scientists lend their expertise to the HiRes Ultra High Energy Cosmic Ray Detector and the Fermi Gamma-ray Space Telescope, and led the Milagro TeV gamma-ray observatory. For more on Milagro, please see page 33.

Radio astronomy

Los Alamos National Laboratory is a founding partner—with the University of New Mexico, the Naval Research Laboratory, the University of Texas, and the National Radio Astronomy Observatory—of the Long Wavelength Array (LWA) initiative. The LWA is a new telescope using low-cost or commodity hardware to explore the radio spectrum between the FM broadcast band (at 88 megahertz) and the ionospheric cutoff (at about 10 megahertz). There are a large number of exciting astronomical goals for this instrument, including a census of the relic universe, supernovae remnant surveys, investigation of the distribution of dark matter as inferred from galaxy clusters, the signature of the Epoch of Re-ionization, and the search for extra-solar planets. A prototype instrument composed of 16 antennas called the Long Wavelength Demonstrator Array began operation recently in southwestern New Mexico. The planned LWA will operate in a similar manner, but will be composed of 13,000 individual antennas, divided into 50 stations, spread throughout the state of New Mexico. For the LWA to perform as planned, a number of difficult problems associated with imaging through the earth's ionosphere must be solved. The Laboratory brings to the collaboration its extensive experience in ionospheric science, image reconstruction, inverse problems, and the management of large data volumes developed for the threat reduction mission.



Milagro was a gamma-ray detector constructed of a large pool of water covered with a light-tight barrier and instrumented with 723 light-sensitive detectors known as photo-multiplier tubes. Shown above is Milagro with the cover inflated, when work was performed on the detector.

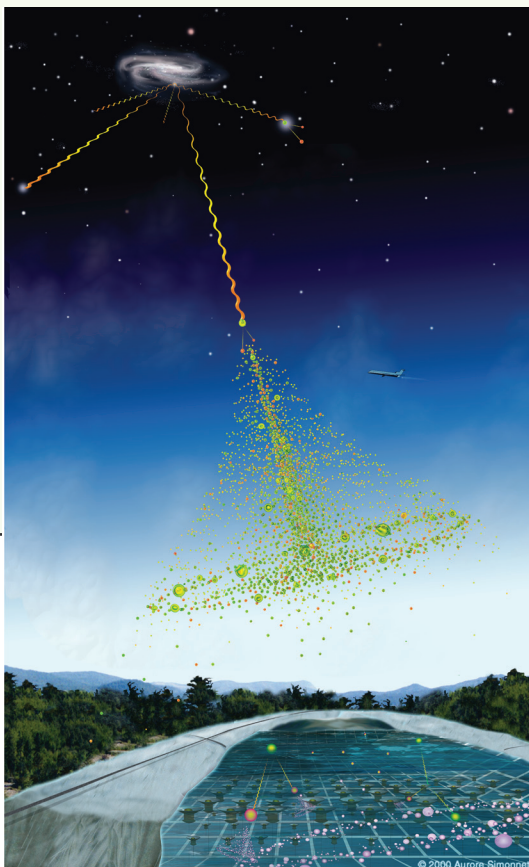
Milagro

An observatory made of water

From 2000 to 2008, the Milagro Gamma-ray Observatory surveyed the overhead sky for sources of very high-energy gamma rays, discovering several new sources and proving this new technique of using water to observe the gamma-ray sky to be effective.

Built and operated by a collaboration of 8 universities and Los Alamos, the Milagro detector was a large pond of water, 80-meters long by 60-meters wide by 8-meters deep, originally created for the Laboratory's Hot Dry Rock geothermal energy program. After the geothermal project ended, the pond was cleaned and covered. Inside were placed sensitive photodetectors on a 3-by-3-meter grid in 2 layers at 1.5 and 7 meters below the surface of the 5 million gallons of specially cleaned and filtered water.

Milagro was funded by the National Science Foundation and the Department of Energy, with support for scientific studies from internal Laboratory research and development resources. Los Alamos, with a successful history of developing water Cherenkov detectors and studying cosmic rays, managed the site and its operation and led many scientific investigations that resulted in peer-reviewed publications.



Milagro's map of the TeV sky clearly showed several previously undiscovered very high-energy gamma-ray sources as well as a diffuse glow from the plane of the Milky Way.

Gamma rays and cosmic rays are detected when they collide with a molecule in the earth's atmosphere to produce a shower of particles, of which some reach the ground. This shower is a thin pancake of particles and secondary gamma rays moving at nearly the speed of light. The plane of the pancake is perpendicular to the direction of the gamma ray or cosmic ray that initiated the shower.

Prior to Milagro, the only successful technique for detecting high-energy gamma-ray showers used large mirrors to focus the small amount of Cherenkov light made by the shower traversing the atmosphere. However, this atmospheric Cherenkov technique requires the mirror to be pointed at a source, which makes it difficult to discover new sources. Also, this technique requires good weather and no sunlight or moonlight for a duty factor of less than 10%, which makes it difficult to find rare transient sources.

Milagro, however, detected showers when they hit the water, and because of its light-tight cover, it operated with a duty factor of more than 95%. Plus, Milagro had a large field of view and could detect showers from angles up to 45 degrees from zenith. In addition, the deep-water detector allowed the background to be rejected, essential for the sufficient sensitivity to detect new gamma-ray sources.

More than 200 billion showers were detected by Milagro and the resulting map of the TeV sky clearly showed several previously undiscovered sources as well as a diffuse glow from the plane of the Milky Way. The new sources are coincident with rapidly spinning neutron stars, called pulsars, in our galaxy. The glow of the Milky Way is due to cosmic rays colliding with the matter in our galaxy to produce gamma rays. While cosmic rays were first discovered in 1912, their origin is still unknown. The discoveries of Milagro are important probes of these cosmic rays, which contain as much energy as the starlight in our galaxy, but have turned out to be much more difficult to understand.

An air shower generated by gamma rays as they traverse the earth's atmosphere and enter the Milagro detector. Illustration by Aurore Simonnett.

Swift

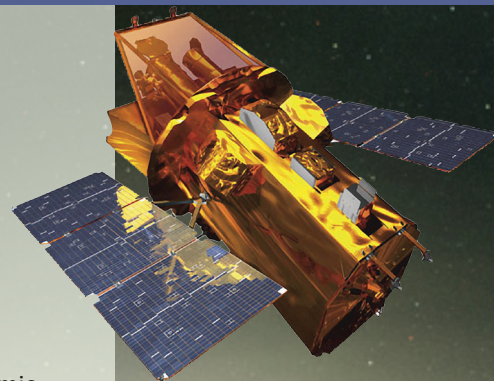
Ever alert to changes in the universe

Swift is a revolutionary space-based observatory designed to unravel the secrets of gamma-ray bursts, nature's most powerful explosions, and to use those explosions to explore the properties of the early universe. Swift is a multi-wavelength NASA observatory that carries three co-aligned telescopes for studying these cosmic explosions and their afterglows: (1) the Burst Alert Telescope (BAT)—a wide field gamma-ray telescope for detecting and localizing the explosion, (2) the sensitive narrow-field X-Ray Telescope (XRT) for imaging and spectroscopic measurements of the x-ray afterglow, and (3) the narrow field Ultra-Violet/Optical Telescope (UVOT) for measuring the optical afterglow. Launched by NASA in 2004, Swift has detected more than 500 gamma-ray bursts and has been extraordinarily successful; enabling, for example, identification of the most distant objects in the universe.

The key to Swift's success is an unprecedented ability to localize gamma-ray bursts while they are still emitting gamma rays and then slew rapidly to point the narrow-field telescopes at that location, in other words—like the capture of prey by the nimble bird that is the mission's namesake—to “catch them on the fly.” Since these fleeting flashes of gamma-ray emission occur at random positions in the sky and typically last from a fraction of a second to about a minute, the Swift mission needed a gamma-ray sky imager and real-time gamma-ray burst localization software to enable the autonomous response. Los Alamos scientists made essential contributions to the conquering of that technical challenge by designing, writing, and testing the real-time gamma-ray burst localization software carried onboard Swift and by helping to design the coded mask for the BAT sky imager. That same localization software provides the gamma-ray burst positions that are relayed to the ground and distributed in seconds to ground-based telescopes around the globe like Los Alamos's robotic RAPTOR telescopes.

Swift has provided us amazing discoveries about the nature of gamma-ray bursts. For example, Swift observations and the observations they enabled by other telescopes have convincingly shown that long duration gamma-ray bursts (those that emit gamma rays for a duration longer than 3 seconds) are generated by the collapse of a rare class of very massive stars to form stellar mass black holes. The distances derived from spectral redshifts of the infrared/optical counterparts indicate that gamma-ray bursts can originate at distances as large as 13.1 billion light years, meaning the gamma-ray burst explosion occurred when the universe was only about 600 million years old. The progenitor stars must be some of the very first stars. Gamma-ray bursts are the birth announcements that signal the formation of the first stellar mass black holes in the universe.

Swift is also providing new insights about extreme explosions in our galaxy and discovering previously unknown types of cosmic explosions. It has detected giant stellar x-ray flares that dwarf those on our sun and intense x-ray/soft gamma-ray flashes from highly magnetized neutron stars (so-called magnetars) in our galaxy. Recently it also discovered evidence for a type of outburst that occurs when a star wanders too close to a massive black hole in the core of a galaxy and is torn apart as it is swallowed by the black hole. As long as the Swift survives on orbit—it should be able to weather the current solar maximum—we can expect it to deliver new insights into extremely violent events in the universe.



NASA's Swift satellite that is designed to catch cosmic gamma-ray bursts “on the fly.” Credit: NASA

Key to Swift's success is an unprecedented ability to localize gamma-ray bursts while they are still emitting gamma-rays and then slew rapidly to point the narrow field telescopes at that location.

An illustration showing a flare from magnetar Swift J195509+261406, which was observed by the Swift spacecraft on June 10, 2007. Credit: NASA/Swift/Sonoma State University/A. Simonnet

Robotic thinking telescopes

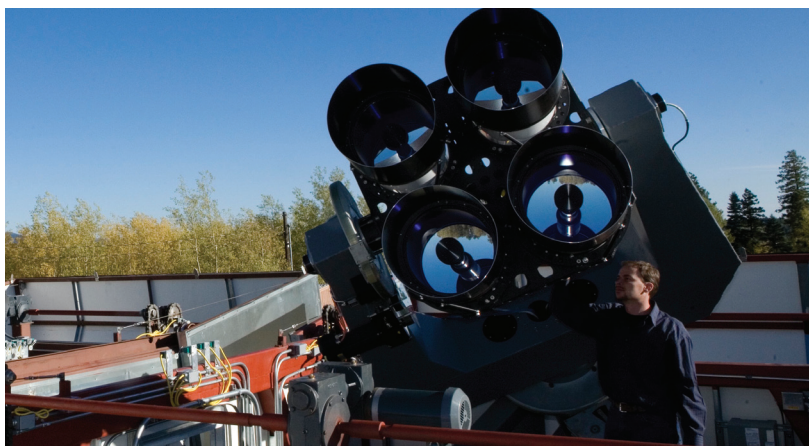
Designing instruments that see and perceive

Time-domain astronomy—the study of the temporal variability of celestial objects—is one of the richest areas for discovery in modern astronomy. And, while the variability of the night sky is still largely unexplored, time-domain astronomy has already had a profound effect on our understanding of the universe by revealing the first evidence for dark energy. In recognition of the power of this technique, NASA, the National Science Foundation, and the DOE Office of Science are making major investments in extensive variability surveys of the night sky. However, humans do not have the attention span, memory, nor reaction time required to monitor huge volumes of data, efficiently recognize the important variations that are often ephemeral and subtle, and promptly respond. These surveys therefore threaten to drown us in a “flood of data,” but leave us “thirsty for knowledge.”

Los Alamos scientists are at the forefront of building autonomous robotic telescopes that take humans “out of the loop” by recognizing important anomalous behavior in the night sky and promptly making real-time follow-up observations. For example, they have constructed and are operating a network of autonomous robotic telescopes—thinking telescopes—that observe the full night sky searching for optical transients, simultaneously monitoring more than 10 million persistent sources, recognizing anomalous behavior, selecting targets for detailed interrogation, and making real-time, follow-up observations—all without human intervention. The construction of these RAPTOR (RAPid Telescopes for Optical Response) telescopes required significant achievements in robotic instrumentation, distributed networks, high-speed data reduction pipelines, and machine learning.

The principal scientific focus of the thinking telescopes effort has been cosmic explosions, particularly gamma-ray bursts. The speed of the RAPTOR telescopes—they are able to slew to any position in the visible night and begin imaging in less than 6 seconds—make them ideal for studying the optical emission during the typical 1 minute or less duration of a gamma-ray burst. For example, Los Alamos astronomers found previously unknown flashes of visible light that have a common origin with the gamma rays. These flashes of visible light are best explained as emission from internal shocks generated as an ultra-relativistic jet punches through a collapsing massive star in the process of forming a black hole. Even though these explosions typically occur at distances measured in billions of light years, the flashes of light can be quite bright. For example, on March 19, 2008, the RAPTOR telescopes detected a flash that for about 10 seconds reached a visual magnitude of 5.4—bright enough to be visible to the naked eye. Spectral measurements of the burst afterglow indicate that the explosion occurred at a distance corresponding to a look back time of 7.5 billion years. GRB 080319b, as the burst is known, therefore shatters all previous records as the most luminous event in the universe ever observed by humankind.

This thinking telescopes technology also has applications much closer to home. Los Alamos scientists are now using the techniques originally developed for finding and responding to astrophysical transients to the finding and tracking of orbital space debris. Space debris is starting to pose a significant hazard to operational satellites. The heavy reliance of our nation on space-based assets, and the rapidly growing number of launches by nations around the globe, is increasingly making the exploration of new solutions for space situational awareness an important focus of work at the Laboratory.



Los Alamos scientists are at the forefront of building autonomous robotic telescopes that recognize important anomalous behavior in the night sky and promptly make real-time follow-up observations.

Los Alamos National Laboratory's ultra-fast, robotic, RAPTOR-T(echnicolor) telescope that can slew and capture simultaneous multi-color images of cosmic explosions anywhere in the visible night sky in less than 6 seconds.

Emulating the explosive universe

Astrophysical models mirror and reveal celestial phenomena

Through leadership in computational science and theoretical research, Los Alamos is at the forefront of developing realistic astrophysical simulations. Through these models Laboratory scientists gain a better understanding of our explosive universe, including supernovae, supermassive black holes and galaxy clusters, and exoplanet formation.

Supernovae simulations

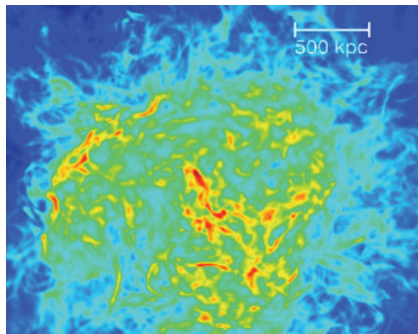
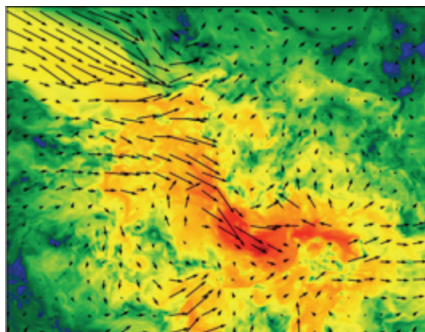
Los Alamos has developed a capability to model supernova explosions from the onset of stellar collapse through the propagation of the supernova remnant, hundreds of years after the explosion. By employing Laboratory expertise in nuclear and neutrino physics, and advances in radiative transport, Los Alamos has developed the first ever three-dimensional, neutrino Monte Carlo transport code. With these, we can produce the highest fidelity explosion simulations in the world. But to understand this physics, we must tie these explosions to the observational diagnostics of supernovae. Our expertise in atomic physics, radiation transport, and turbulent mixing has led to the development of a supernova theoretical light-curve factory at Los Alamos. We are now modeling transients for astrophysicists worldwide and providing theoretical models for NASA's Nuclear Spectroscopic Telescope Array, Swift, the James Webb Space Telescope, Wide-Field Infrared Survey Telescope satellites, the Palomar Transient Factory, the Panoramic Survey Telescope & Rapid Response System, and a number of individual observational programs. With papers in *Nature*, *Science*, and a host of astrophysical journals, the Laboratory is a world leader in theoretical study of supernova explosions.

Exoplanet astrophysics

The discovery of more than 700 exoplanets in the past 15 years has stimulated an increased interest in the basic processes regulating planet formation and planetary system evolution. This includes at Los Alamos, which has a long history in the modeling of accretion disks around stars and other compact objects. Using sophisticated multidimensional hydrodynamic codes, developed at the Laboratory, Los Alamos researchers are investigating the formation and migration of protoplanets in their nascent disks. Our numerical simulations show that the fate of protoplanet embryos depends critically on disk viscosity and a detailed understanding of wave/shock damping in a strong shear flow environment. In addition, Los Alamos's original study on the formation and evolution of Rossby vortices in disks has also opened up new opportunities for investigating the formation of multiple planets and their migration. An exciting future prospect is the opportunity to compare Los Alamos's simulations of protoplanetary disks harboring giant planets with the upcoming observations by the Atacama Large Millimeter Array and the Expanded Very Large Array (EVLA).

Supermassive black holes and galaxy clusters

Los Alamos researchers conduct cosmological hydrodynamic simulations in an effort to understand the mass supply and transport that forms supermassive black holes in the cosmological environments. Their studies show that magnetic field generation in disks around these objects will lead to the formation of powerful magnetically dominated jets and radio lobes, which create important feedback effects on the surrounding medium, especially those observed cavities in the intra-cluster medium (ICM) as revealed by the Chandra X-ray Observatory. In collaboration with the University of California, San Diego, Los Alamos researchers have developed the state-of-the-art cosmological magnetohydrodynamic (MHD) simulation code to study the formation of galaxy clusters and the evolution of magnetic fields in these clusters on cosmological scales. These simulations have been compared with Chandra observations in x-rays and Very Large Array observations in radio for both intensity measurement and Faraday rotation measurements. A collaboration with scientists from the University of New Mexico and the National Radio Astronomy Observatory has yielded new observations using the EVLA that further constrain the key parameters in the simulations. These studies are essential in understanding the physical conditions of galaxy clusters to provide the underpinning physics for use as a cosmology and astrophysics laboratory for "precision cosmology."



The formation of a galaxy cluster (left) showing MHD turbulence generation by multiple mergers of smaller galaxy groups. During this formation, magnetic fields are amplified by the ICM turbulence through a small-scale dynamo process (right).

Simulating QCD

A fundamental theory of nature, on petascale computers

By harnessing the incredible computing speed of the Laboratory's supercomputers, Los Alamos scientists are digging deeper into the universe's past and aiding in the quest to develop a deeper understanding of the fundamental nature of matter.

In the evolutionary history of the universe, an extreme state of matter, the quark-gluon plasma (QGP), existed in the first few microseconds after the Big Bang. Since that time, the fundamental constituents of matter, called quarks and gluons, are only seen as bound states called hadrons; confined by the strong force that is described by a mathematical theory called quantum chromodynamics (QCD).

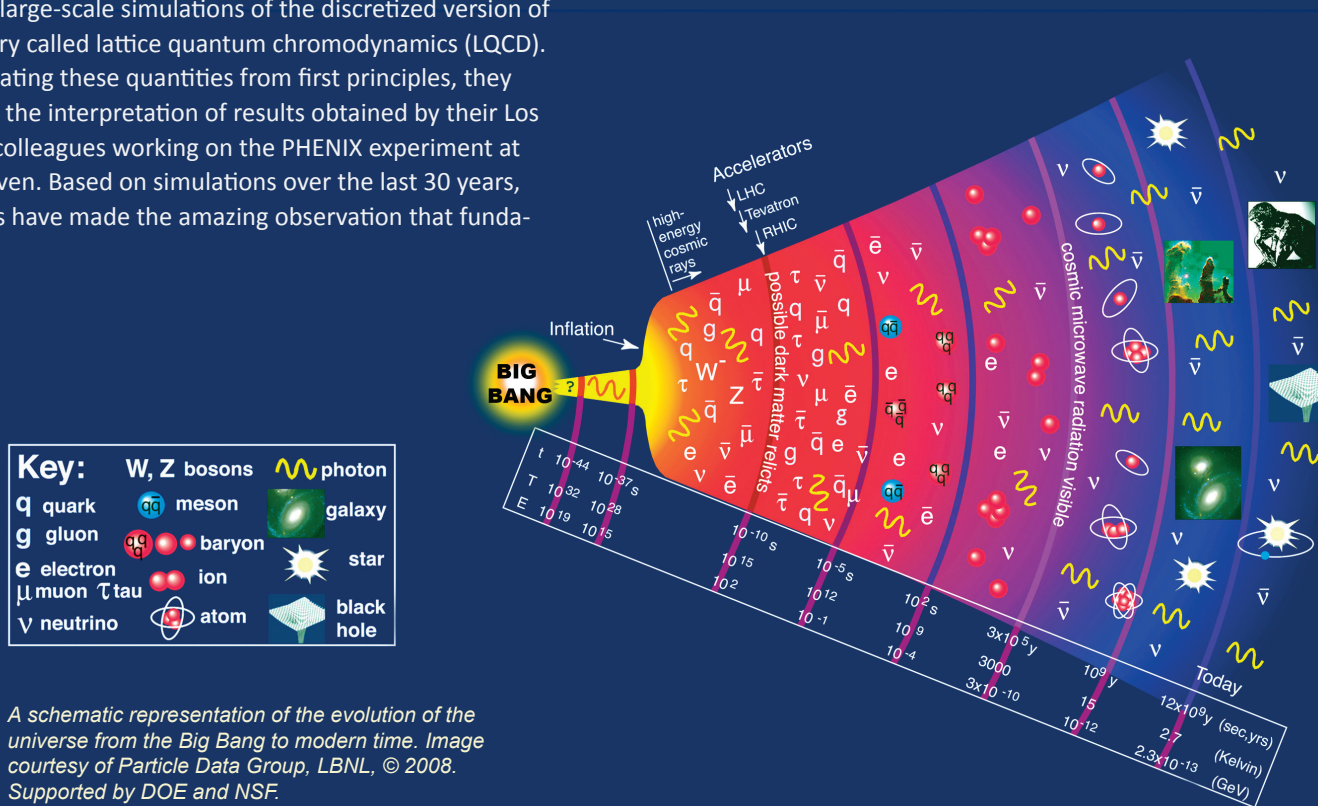
Scientists can create these extreme conditions of temperature and energy density by colliding relativistic heavy ions in experiments at Brookhaven National Laboratory in the United States and CERN in Europe. In these experiments, the QGP exists for a short period of time, 10^{-13} seconds, before it cools and matter freezes into hadrons that are then observed in sophisticated detectors.

The equation of state of QCD, viscosity, and the transition temperature from the QGP to hadronic matter are important factors in experiment analysis. To help define these properties of QCD, theoretical physicists at Los Alamos conduct large-scale simulations of the discretized version of the theory called lattice quantum chromodynamics (LQCD). By calculating these quantities from first principles, they facilitate the interpretation of results obtained by their Los Alamos colleagues working on the PHENIX experiment at Brookhaven. Based on simulations over the last 30 years, scientists have made the amazing observation that funda-

mental properties of nature can be accurately calculated by modeling, in a computer, the universe with size reduced to 10–20 times a typical hadron, 10^{-12} centimeters. The universe can then be studied by varying 6 parameters, 5 quark masses and the coupling constant, around the values that nature chose.

With the advent of petaflop supercomputing, capable of processing vast sums of data in timely fashion, LQCD scientists are poised to make precise first principle calculations of the theory of quarks and gluons, in a regime where all known analytical methods fail because of the large coupling constant defining QCD.

Los Alamos scientists and their U.S.-wide collaboration have recently undertaken the important calculation of mapping the equation of state, i.e., behavior of the energy density and the pressure as a function of the temperature over the range 1.5–8.0 trillion degrees Kelvin that is accessible in experiments. The quality of existing results is already good enough to allow their experimental colleagues to model the evolution of matter, all the way from the QGP formed in the collision to the final free-streaming gas of hadrons captured in the detectors, and thereby understand QCD in its most extreme state.





NPAC, into the future

The nuclear physics, particle physics, astrophysics, and cosmology program at Los Alamos has evolved since the days when LAMPF was a major nuclear physics facility. We have been able to take advantage of the neutron and protons beams at LANSCE to do important and unique experiments. Our program is evolving to better respond to the needs of Los Alamos National Laboratory's national security mission and continues to strive for a world-class basic research enterprise in this essential area of research.

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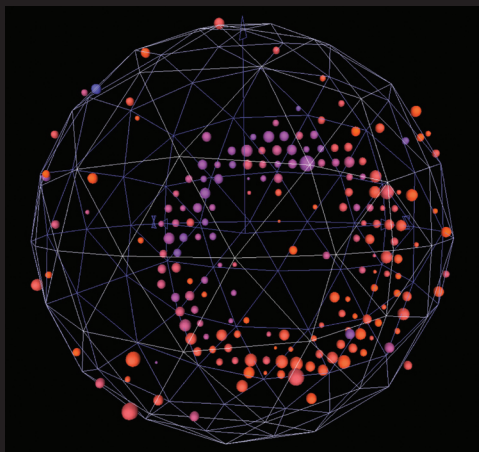
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Experimental Physical Sciences mission

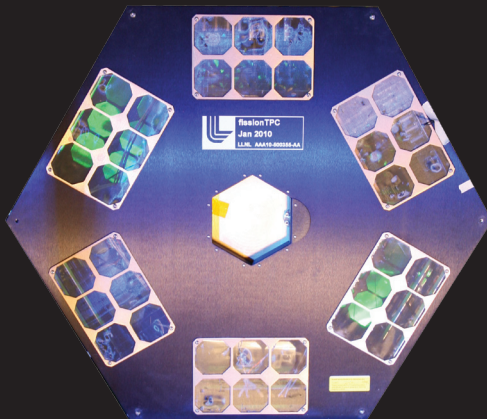
We develop and apply a broad set of capabilities in materials science and experimental physics to programs and problems of national importance. The success of our science requires world-class research and processing facilities, including our Los Alamos-based national user facilities—the Los Alamos Neutron Science Center, the Center for Integrated Nanotechnologies, and the National High Magnetic Field Laboratory.

Experimental Physical Sciences vision

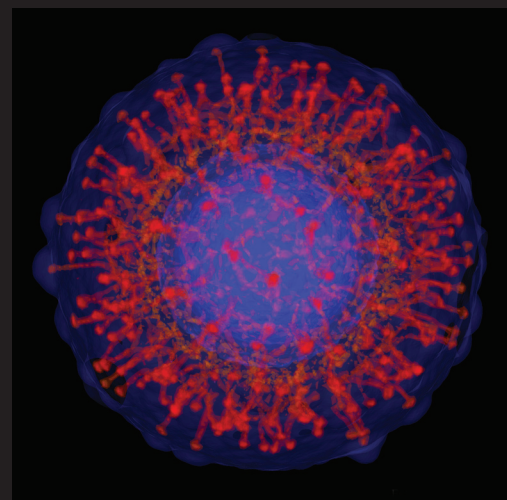
We cultivate a responsive, high-performance staff that conducts innovative, cross-disciplinary research and development that produces breakthrough solutions to the most pressing national security challenges.



Nuclear and Particle Physics



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Experimental Physical Sciences

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